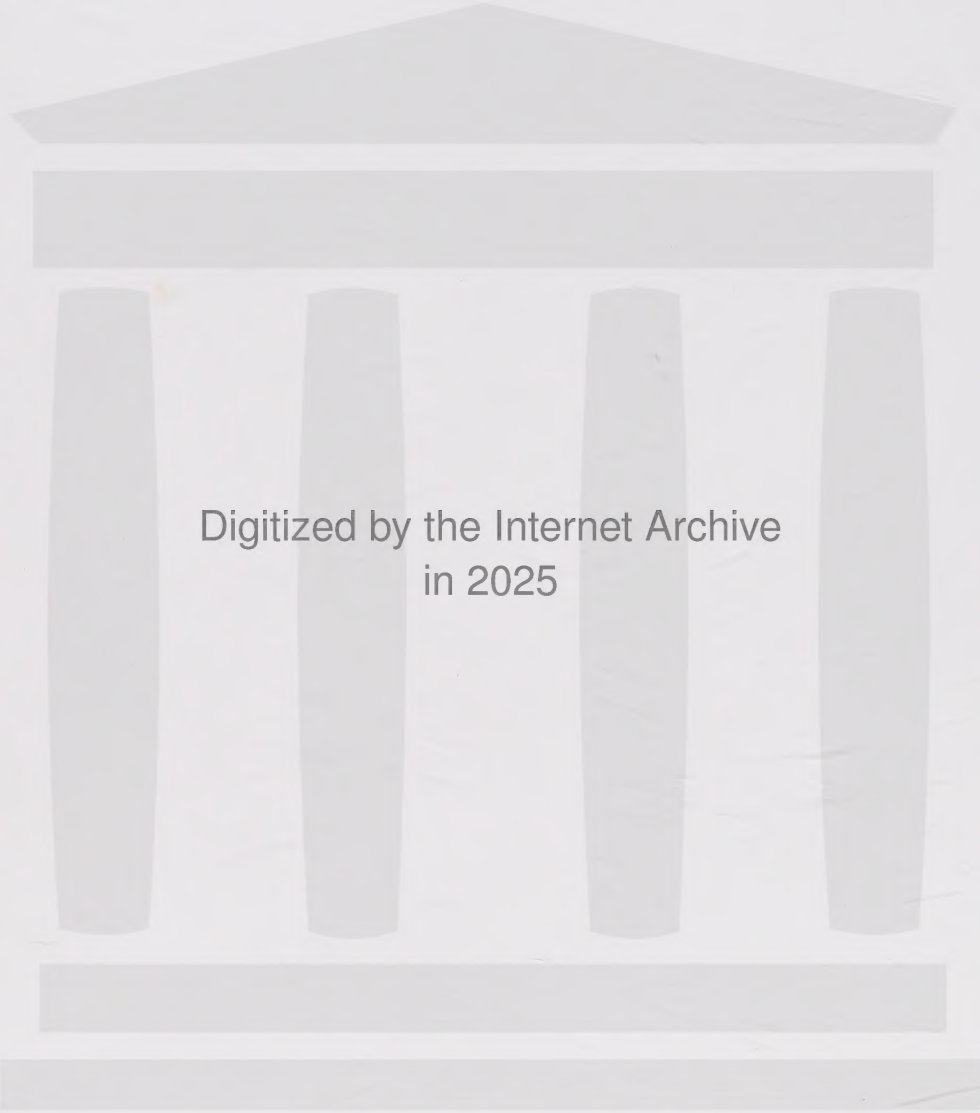


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KINDS AND ABUNDANCE OF FISH LARVAE IN THE EASTERN TROPICAL PACIFIC ON THE SECOND MULTIVESSEL EASTROPAC SURVEY, AND OBSERVATIONS ON THE ANNUAL CYCLE OF LARVAL ABUNDANCE

ELBERT H. AHLSTROM¹

ABSTRACT

This is the second and concluding paper dealing with kinds and abundance of fish larvae in the eastern tropical Pacific based on collections made on EASTROPAC survey cruises. Main emphasis is placed on the composition and abundance of fish larvae on the second multivessel EASTROPAC cruise, occupied by three research vessels during August-September 1967. This cruise, spaced 6 months after EASTROPAC I, affords interesting comparisons of composition and relative abundance of fish larvae during two contrasting periods of the year. Counts of fish larvae per haul on EASTROPAC II were about 50% greater than on EASTROPAC I; species composition, however, was strikingly similar in the two surveys.

A portion of the EASTROPAC pattern, lying between long 119° to 98°W and lat 20°N to 3°S, was covered on four additional monitoring cruises—providing coverage of this more restricted area on six cruises, spaced at 2-month intervals, between February 1967 and January 1968. Essentially the same kinds of fish larvae were taken on each of the six coverages of the monitoring pattern, and for most species the range in relative abundance during the annual cycle was 3× or less.

This report deals with the composition and relative abundance of fish larvae in the eastern tropical Pacific Ocean collected on the second multivessel survey cruise made as part of EASTROPAC, during August-September 1967. For brevity, the cruise is referred to in this report as EASTROPAC II (ETP II). This cruise, conducted 6 months after EASTROPAC I (ETP I), deals with the composition of fish larvae at a contrasting period of the annual spawning cycle in tropical waters (Ahlstrom, 1971).

Three research vessels participated in ETP II: *Washington* operated by the Scripps Institution of Oceanography occupied the outer pattern, *Undaunted* of the National Marine Fisheries Service occupied the middle pattern, and *Rockaway* operated by the Coast Guard took the inner pattern (Figure 1).

The coverage during ETP II was less extensive than that of the four vessels of ETP I. One major line of stations of ETP I was omitted from ETP II, that along long 126°W, and the coverage below the equator was abbreviated in the two outer patterns, with lines ending at lat 10°S or 5°S.

Comparison of the composition, relative abundance, and distributions of fish larvae at different periods of the year in tropical waters is a primary objective of this report. The major comparison is with fish larvae obtained on ETP I (Ahlstrom, 1971); all of the 355 ETP II collections and an equivalent number of ETP I collections can be used to show similarities and differences in the composition of the larval fish fauna during two contrasting periods of the year.

A portion of the EASTROPAC pattern was occupied by the National Marine Fisheries Service research vessel, *David Starr Jordan*, on

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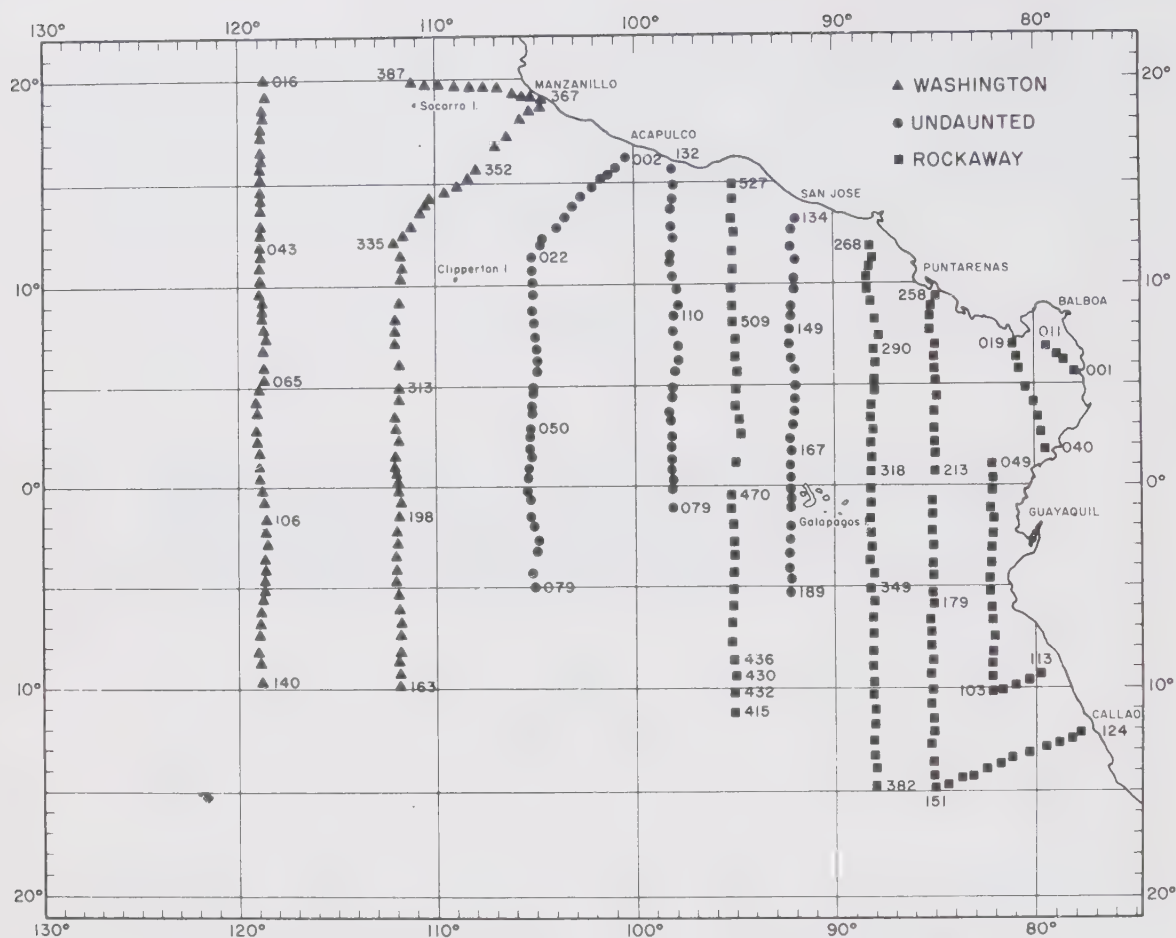


FIGURE 1.—Location of plankton stations occupied by three research vessels participating in the second multivessel EASTROPAC survey (ETP II). Symbols for vessels indicated in legend above. Samples collected by *Washington* are numbered as 45,000 series (for example 45.016, 45.140, 45.387), samples from *Undaunted* as 46,000 series, from *Rockaway* as 47,000 series.

monitoring cruises, spaced at bimonthly intervals between the multivessel cruises; coverages equivalent to the monitoring pattern were summarized for ETP I and ETP II, in order to compare the results of six bimonthly coverages of the same area (Figure 2). The monitoring pattern lacked coverage in the nearshore portion of the EASTROPAC pattern that was occupied by the inner vessel on multivessel surveys. Additional seasonal information about composition and relative abundance of fish larvae in this area was supplied by a "zig-transect" of 50 sta-

tions occupied by the RV *Oceanographer* of the Environmental Science Services Administration during November 1967—2 to 3 months after ETP II coverage of this area (Figure 2).

The methods of making zooplankton hauls on ETP II were identical to those previously described for ETP I (Ahlstrom, 1971). This paper deals solely with collections obtained from oblique hauls made with a net, 1-m mouth diameter, constructed of 505 μ nylon (Nitex) cloth, with approximately a 5:1 ratio of effective straining surface, i.e., pore area to mouth area.

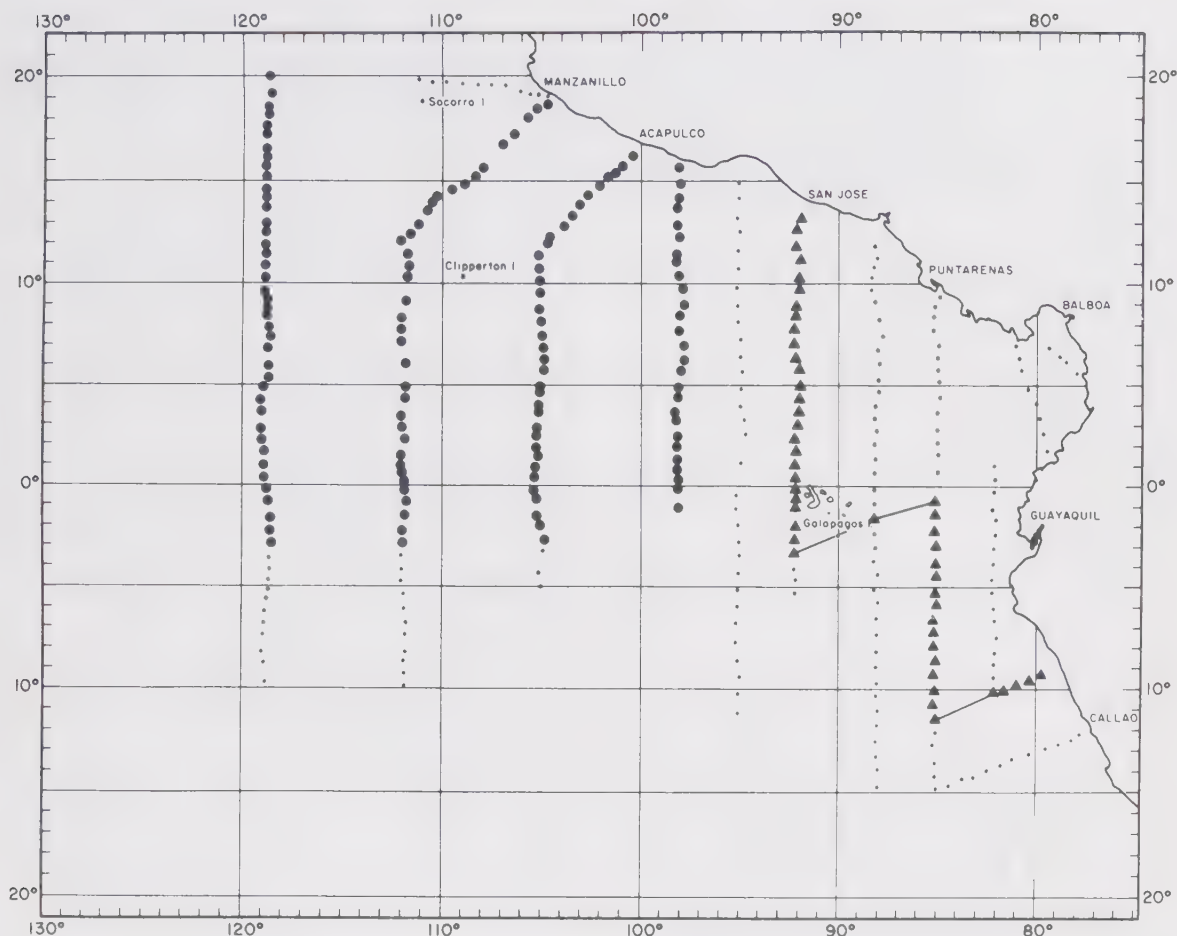


FIGURE 2.—Location of monitoring pattern (large solid circles), occupied between multivessel EASTROPAC cruises at 2-month intervals by *David Starr Jordan*, and of zig-transect pattern (triangles) occupied by *Oceanographer* during November 1967, superimposed on ETP II pattern.

As on ETP I, this net was paired in an assembly frame with a finer-meshed 0.5-m net. Each tow attempted to obtain a uniform sampling of zooplankton in the water column between the surface and approximately 200-m depth. The net assembly was lowered to depth by paying out 300 m of towing cable and then retrieved at a uniform rate. The depth reached by the net was estimated from the angle of stray (departure from the vertical) of the towing cable. The average depths of haul taken by the three research vessels are summarized in Table 1. Only slightly

over two-thirds of the hauls were lowered to depths of 200 m or more and about one-eighth were taken at depths shallower than 180 m. Based on variation in depths sampled, speed of hauling was controlled less consistently on ETP II as compared with ETP I.

Four plankton collections were made each day with the paired net-assembly, at about 6-hr intervals. Timing of hauls was not coordinated between research vessels (Table 2). Usually *Rockaway* spaced the four hauls at approximately 0500, 1030, 1700, and 2300; hauls from *Wash-*

TABLE 1.—Depths of paired oblique plankton hauls taken by the three research vessels in EASTROPAC II (net lowered by paying out 300 m of towing cable).

Average depth of haul (m)	Number of hauls taken at each depth interval from			
	Washington 45,000 Series	Undaunted 46,000 series	Rockaway 47,000 Series	All vessels
80.1-90.0	--	1	--	1
90.1-100.0	--	--	--	--
100.1-110.0	--	--	--	--
110.1-120.0	--	1	--	1
120.1-130.0	--	2	--	2
130.1-140.0	1	--	--	1
140.1-150.0	1	--	3	4
150.1-160.0	2	4	1	7
160.1-170.0	--	5	4	9
170.1-180.0	7	4	6	17
180.1-190.0	6	4	3	13
190.1-200.0	24	16	14	54
200.1-210.0	36	22	52	110
210.1-220.0	28	28	56	112
220.1-230.0	5	6	7	18
230.1-240.0	1	--	1	2
240.1-250.0	--	--	1	1
250.1-260.0	--	--	1	1
260.1-270.0	--	2	--	2
Total	111	95	149	355

TABLE 2.—Hour of day that paired oblique plankton hauls were made from the three research vessels participating in EASTROPAC II (midtime of haul used).

Hour of day	Number of hauls taken during each hour of the day			
	Washington	Undaunted	Rockaway	All vessels
0001-0100	10	10	8	28
0101-0200	4	0	1	5
0201-0300	1	0	3	4
0301-0400	0	1	3	4
0401-0500	0	10	14	24
0501-0600	5	8	15	28
0601-0700	12	3	4	19
0701-0800	5	1	0	6
0801-0900	2	0	1	3
0901-1000	1	0	6	7
1001-1100	1	0	21	22
1101-1200	10	14	6	30
1201-1300	11	11	1	23
1301-1400	3	0	1	4
1401-1500	3	0	2	5
1501-1600	2	0	12	14
1601-1700	0	0	16	16
1701-1800	10	22	4	36
1801-1900	9	3	1	13
1901-2000	5	0	0	5
2001-2100	2	0	3	5
2101-2200	1	0	5	6
2201-2300	0	0	11	11
2301-2400	14	12	11	37
Total	111	95	149	355

ington usually were taken at approximately 0630, 1200, 1800, and 2400; and hauls from *Undaunted* at 0500, 1200, 1730, and 2400. At least some hauls were taken during every hour of the day.

EFFECTIVENESS OF SAMPLING FISH LARVAE IN DAYLIGHT HAULS AS COMPARED WITH NIGHT HAULS

Catches of fish larvae for selected families in day hauls compared to night hauls or to hauls taken within ± 1 hr of sunrise or sunset are summarized in Table 3. For all categories of larvae combined, the catch was 212.0 larvae per daytime haul and 480.4 larvae per night haul, a difference in catch of $2.27\times$. Hauls taken within ± 1 hr of sunrise or sunset had an average catch of 347.0 larvae, intermediate between day and night catches.

Difference between day and night collections was somewhat less than for ETP I; on that survey the average count of larvae in night hauls was $2.76\times$ as many as in day hauls (Ahlstrom 1971, Table 4). On both surveys gonostomatid larvae had the most marked differences in catches between night hauls and day hauls: $4.3\times$ as many, on the average, in night collections compared with day on ETP I, $2.9\times$ as many in night collections on ETP II. Night-day differences in catch per haul of myctophid larvae were less marked between the two surveys: $3.0\times$ on ETP I as compared with $2.6\times$ on ETP II. Night-day differences in average catches of bathylagid larvae were similar on the two multi-vessel surveys: $1.5\times$ as many per haul on the average, in night collections compared with day collections. Sternoptychid larvae, which were sampled almost as well in day hauls as in night hauls on ETP I, showed a somewhat greater night-day difference on ETP II: $1.7\times$ for ETP II as compared with $1.2\times$ for ETP I.

Scombrid larvae were taken in lesser numbers per haul in both day and night hauls on ETP II compared with ETP I; in contrast to ETP I, however, (where a night-day difference of $3.7\times$ was observed) no difference was obtained in night and day collections on ETP II.

TABLE 3.—Comparison of occurrences (positive hauls) and catches (original counts) of fish larvae in day hauls, night hauls, and hauls taken within 1 hr of sunrise or sunset, summarized for selected families.

Family or group	Day hauls			Night hauls			N/D	Hauls within ± 1 hr of sunrise or sunset			Total hauls		
	Number positive hauls	Total larvae	Average number per occupancy (D)	Number positive hauls	Total larvae	Average number per occupancy (N)		Number positive hauls	Total larvae	Average number per occupancy	Number positive hauls	Total larvae	Average number per occupancy
Bathylogidae	114	1,802	13.1	110	2,607	20.2	1.5	74	1,482	16.8	298	5,891	16.6
Gonostomatidae	131	4,896	35.5	125	13,264	102.8	2.9	86	6,095	69.3	342	24,255	68.3
Sternophychidae	104	2,005	14.5	104	3,136	24.3	1.7	69	2,244	25.5	277	7,385	20.8
Chauliodontidae	18	68	0.5	23	86	0.7	1.4	15	53	0.6	56	207	0.6
Idiacanthidae	58	211	1.5	70	307	2.4	1.6	53	277	3.1	181	795	2.2
Other stomiatidei	78	412	3.0	83	447	3.5	1.2	54	248	2.8	215	1,107	3.1
Myctophidae	136	13,847	100.3	128	33,167	257.1	2.6	88	16,995	193.1	352	64,009	180.3
Paralipidae	84	851	6.2	95	1,110	8.6	1.4	68	574	6.5	247	2,535	7.1
Scopelarchidae	47	83	0.6	53	139	1.1	1.8	34	76	0.9	134	298	0.8
Melamphaidae	112	463	3.4	105	581	4.5	1.3	67	321	3.6	284	1,365	3.8
Bregmaceroidae	59	847	6.1	59	1,138	8.8	1.4	42	1,077	12.2	160	3,062	8.6
Exocoetidae	27	104	0.8	18	22	0.2	0.2	14	20	0.2	59	146	0.4
Trachipteridae	13	14	0.1	22	27	0.2	2.0	11	18	0.2	46	59	0.2
Apogonidae	21	112	0.8	26	94	0.7	0.9	19	77	0.9	66	283	0.8
Bramidae	20	29	0.2	28	43	0.3	1.5	19	24	0.3	67	96	0.3
Chiasmodontidae	31	60	0.4	43	106	0.8	2.0	26	71	0.8	100	237	0.7
Coryphaenidae	43	60	0.4	40	75	0.6	1.5	26	53	0.6	109	185	0.5
Nomeidae	83	483	3.5	85	642	5.0	1.4	61	335	3.8	229	1,460	4.1
Scombridae	14	92	0.7	25	94	0.7	1.0	16	62	0.7	55	248	0.7
Other identified	114	1,278	9.3	120	3,649	28.3	3.0	79	959	10.9	313	5,886	16.6
Unidentified	69	260	1.9	65	426	3.3	1.7	48	176	2.0	182	862	2.4
Disintegrated larvae	118	1,272	9.2	98	814	6.3	0.7	72	728	8.3	288	2,814	9.8
Total fish larvae	138	29,249	212.0	129	61,974	480.4	2.27	88	31,962	363.1	355	123,185	347.0

WATER TEMPERATURES ON EASTROPAC II

Water temperatures were available at 1-m intervals from the surface to about 750-m depth for each station at which an STD was used for determination of salinity and temperature. I selected three depths for tabulation and study: surface, 10 m, and 50 m. STD readings were available for 347 of the 355 plankton stations taken on ETP II. A chart of surface temperature for ETP II will be included in the EASTROPAC Atlas.

To facilitate discussion of distributions of fish larvae, I have found it convenient to divide the EASTROPAC area into quadrants with the north-south division at the equator and the east-west division at long 100°W. I will use these divisions when discussing distribution of temperatures on ETP II, except for separating out a narrow band of water at the equator (lat 2°N to 2°S). Within a quadrant the temperatures are summarized by 5° latitude, except near the equator (Table 4).

In some parts of the ETP II pattern, the thermocline was considerably deeper than 50 m, so that the temperature at 50 m was similar to that at the surface. At a few stations in the northeast quadrant, where the thermocline was almost at the surface, the temperature at 10 m was 5° to 10°C lower than at the surface. At most stations in this quadrant the thermocline was considerably shallower than 50-m depth, as attested by marked differences in temperature between

the surface and 50 m (Table 5). Mixed layer depths on ETP II were illustrated in Blackburn, Laurs, Owen, and Zeitzschel (1970)—Figure 7 on page 27. A brief summary of the temperature structure is given by quadrant.

NORTHEAST QUADRANT, EXCEPT WITHIN 2° LATITUDE OF EQUATOR

Surface temperatures in this quadrant were high, ranging between 25.4° and 29.8°C (average 27.2°C). Temperatures at 10 m were usually the same or within $\pm 0.5^\circ\text{C}$ of the surface, although 10 stations showed differences of more than 1°C and 7 of those were 4.6° to 10.1°C lower. These marked differences are indications of very shallow thermoclines; five contiguous stations along long 88°W offshore from Puntarenas, Costa Rica, had such near-surface thermoclines.

At most stations the thermocline was shallower than 50 m; at 79 of 91 stations, the temperature at 50 m was 5° to 15°C lower than at the surface, and at half of these the temperature was between 10° to 15°C lower at 50 m.

NORTHWEST QUADRANT, EXCEPT WITHIN 2° LATITUDE OF EQUATOR

Surface temperatures in this quadrant, 24.8° to 29.7°C (average 27.6°C), were similar to those of the inshore quadrant. Highest surface temperatures, averaging 28.3°C, were encoun-

TABLE 4.—Range of temperatures at surface, 10 m, and 50 m summarized by 5° latitude or smaller intervals for both offshore (long 100°-119°W) and inshore (coast to long 98°W) for EASTROPAC II.

Latitude	Offshore: long 100°-119°W				Inshore: coast to long 98°W			
	No. stn.	Range in temperature (°C) at:			No. stn.	Range in temperature (°C) at:		
		Surface	10 m	50 m		Surface	10 m	50 m
15°-20°N	32	25.7-29.7	25.5-29.6	17.7-28.6	1	29.8	29.6	23.1
10°-15°N	30	26.3-29.8	26.0-29.4	16.7-27.9	23	26.4-29.7	19.7-29.6	14.0-26.7
5°-10°N	20	25.8-27.7	25.8-27.8	16.5-27.4	42	25.8-28.9	16.3-28.9	13.5-23.6
2°-5°N	15	24.8-26.6	24.8-26.4	20.3-26.2	25	25.2-26.8	25.3-27.0	15.2-25.9
Total 2°-20°N	97	24.8-29.7	24.8-29.6	16.5-28.6	91	25.2-29.8	16.3-29.6	13.5-26.7
Equator 2°N-2°S	20	19.5-25.0	19.0-25.0	15.7-22.4	30	16.4-25.9	15.6-25.9	13.7-17.4
2°-5°S	14	20.6-23.0	20.5-23.0	14.0-22.6	19	18.4-22.2	17.4-21.9	14.2-20.2
5°-10°S	16	22.9-24.9	22.7-24.9	22.4-24.9	30	16.3-21.5	16.3-21.5	14.6-21.4
10°-15°S	0	--	--	--	30	15.4-21.4	15.1-21.4	13.9-21.2
Total 2°-15°S	30	20.6-24.9	20.5-24.9	14.0-24.9	79	15.4-22.2	15.1-21.9	13.9-21.4

TABLE 5.—Summary of temperature differences within upper 50 m depth (differences in temperature at the surface and at two selected depths—10 m and 50 m) summarized by quadrants.

Area	No. stn.	Difference in temperature at the surface and at 10-m depth					Difference in temperature at the surface and at 50-m depth				
		0°C	0.1°-0.5°C	0.6°-1.0°C	1.1°-5.0°C	5.1°-10.1°C	0°C	0.1°-1.0°C	1.1°-5.0°C	5.1°-10.0°C	10.1°-15.0°C
NE Quadrant (lat 2°-16°N, coast to long 98°W)	90	38	39	3	4	6	0	2	9	40	39
NW Quadrant (lat 2°-20°N, long 100-119°W)	97	65	26	5	1	0	6	14	46	27	4
Equator (lat 2°N-2°S, coast to long 98°W)	30	19	8	1	2	0	0	0	10	19	1
Equator (lat 2°N-2°S, long 100-119°W)	20	9	9	2	0	0	0	1	13	6	0
SE Quadrant (lat 2°-15°S, coast to long 98°W)	79	61	15	2	1	0	20	31	27	1	0
SW Quadrant (lat 2°-10°S, long 100-119°W)	30	17	12	1	0	0	9	15	5	1	0

tered between lat 15° and 20°N. Temperatures at 10 m were usually the same as at the surface, and in only one instance was the difference as great as 1.3°C. Temperatures at 50 m were identical to, or within 1°C of, the surface temperatures at about 20% of the stations, all located between lat 2° and 10°N—these were stations with deep thermoclines. Temperature differences between the surface and 50 m exceeded 5°C at about 35% of the stations.

EQUATOR, LAT 2°N TO 2°S

Surface temperatures were variable, with 9.5°C range (16.4° to 25.9°C). Lowest surface temperatures, undoubtedly resulting from upwelling, were encountered seaward of the Galapagos Islands, between long 92° and 98°W, lat 0.5°N to 2.0°S, but cold water was also encountered farther offshore. Thermoclines were shallow at most stations inshore from the Galapagos Islands, the difference between surface and 50 m exceeded 5°C at about 63% of the stations, but the surface water was warmer than offshore.

SOUTHEAST QUADRANT, EXCEPT WITHIN 2° LATITUDE OF EQUATOR

Water temperatures were much lower in this quadrant than in the northeast quadrant. Few

surface temperatures were as high as 20°C, and the average surface temperature was 18.7°C. The thermocline was usually deep. At 65% of the stations the temperature at 50 m was the same as that at the surface or was not more than 1°C colder.

SOUTHWEST QUADRANT, EXCEPT WITHIN 2° LATITUDE OF EQUATOR

Surface temperatures ranged from 20.6° to 24.9°C (average 21.0°C). Temperatures at 10 m were usually the same as that at surface or within 0.5°C. Temperatures at 50 m were identical to the surface at 30% of stations and within 1°C of the surface temperature at 80% of stations, indicative of a region of deep thermocline.

In summary, water temperatures were much higher north of the equator, than south of the equator. Surface temperatures averaged 8.5°C higher in the northeast quadrant than in the southeast quadrant. Offshore the differences were almost as great; surface temperatures averaged 6.6°C higher in the northwest quadrant than in the southwest quadrant.

As noted in the paper dealing with ETP I collections, information is mostly lacking on depth distribution of fish larvae in the eastern tropical Pacific. Because of the marked variation in depth of thermocline encountered in different

parts of the EASTROPAC pattern, ranging from near-surface to deep, it is anticipated that depth distribution of larvae will be markedly affected by the temperature structure. A carefully planned study of depth distribution of larvae in the eastern tropical Pacific in relation to temperature and thermocline depth is badly needed. Lacking this, it is difficult to meaningfully relate larval distributions to temperature.

A REVIEW OF SIGNIFICANT PAPERS DEALING WITH ADULT FISHES OF THE EASTROPAC AREA

A working knowledge of the adult fishes of an oceanic region is a necessary prerequisite to meaningful study of the fish larvae of that region. Most larval series, initially, are established by working backwards from larger identified specimens (late-larvae or early juveniles) to early-stage larvae. Until recently shore fishes of the eastern tropical Pacific were much better known than deep-sea fishes, e.g., studies by Meek and Hildebrand (1923, 1925, 1928) for Panama and Hildebrand (1946) for Peru. Shore fishes, however, were not an important element of the EASTROPAC ichthyoplankton.

A major contribution to our knowledge of eastern Pacific fishes was made by Garman (1899), who worked up the fishes collected on the *Albatross* Expedition of 1891 to the west coasts of Mexico, Central and South America, and off the Galapagos Islands. Garman dealt with 180 species of fish, most new to science; about a third of these were pelagic, oceanic fishes. Included among the latter are the two most common pelagic fishes, *Diogenichthys laternatus* and *Vinciguerrria lucetia*, in the eastern tropical Pacific, based on their abundance as larvae.

The second oceanographic expedition of the *Pawnee* to the eastern Pacific in 1926 added materially to our knowledge of the deep-sea fishes. Several of the species described by Parr (1931) from these collections are common as larvae in EASTROPAC plankton hauls, including *Bathylagus nigrigenys*, *Diaphus pacificus*, *Lampanyctus*

idostigma, *L. parvicauda*, and *Scopelarchoides nicholsi*.

The New York Zoological Society sponsored several expeditions to the eastern Pacific which stimulated papers on Pacific Myctophidae by Beebe and Vander Pyle (1944) and on ceratioid fishes by Beebe and Crane (1947). The paper on myctophids contains information on taxonomy, biology, and zoogeography of 24 species of myctophids of which none were new. The paper by Beebe and Crane on deep-sea ceratioid fishes dealt with 24 species belonging to six families, of which 10 were new.

The ceratioid fishes of the Gulf of Panama had received attention previously: the Danish research vessel *Dana* had occupied several very productive stations in the Gulf of Panama in 1922, from which Regan (1926) described 18 species of ceratioids, mostly new. Bertelsen (1951) reported taking early life history stages of 23 kinds of ceratioids from the Gulf of Panama in *Dana* collections from its round-the-world expedition of 1928-30.

Information on fishes off Peru was obtained on the Yale South American Expedition of 1953. Morrow (1957a) gave an annotated list of 104 shore fishes, 21 new to the Peruvian fauna, and Morrow (1957b) gave an annotated list of 18 mid-depth fishes.

Bussing (1965) reports on 15 pelagic trawl hauls made on *Eltanin* cruises taken off the South American coast in 1962 and 1963 between lat 3° and 35°S. The collections contained 100 species, representing 33 families. Four trawl hauls were made within the EASTROPAC area; only one yielded substantial numbers of specimens. This was *Eltanin* Station 34 at lat 7°45' to 7°48'S, long 81°23'W, from which 45 species were obtained.

Haedrich and Nielsen (1966) provided annotated identifications of 32 species (21 families) of fishes from stomachs of *Alepisaurus* collected at 19 stations by exploratory longline fishing from the Japanese RV *Shoyo Maru*. Four collections were obtained within the EASTROPAC area, and the other 15 between lat 20° and 40°S.

Craddock and Mead (1970) reported on collections made along two transects through the

southern portion of the Peru Current off Chile at lat 34°S. They provide annotated identifications of 133 species. Although these transects were south of the EASTROPAC area, many of the species also occur in the EASTROPAC area.

Parin (1971) reports on collections of mid-water fishes of the Peru Current zone collected on the fourth cruise of RV *Akademik Kurchatov*. He lists about 150 species representing 33 families. Collections were obtained between lat 5°N and 30°S, in a broad coastal band, extending offshore to long 90°W. Distributions are illustrated for 24 species.

In addition to the above, a number of references dealing with particular species of genera or families of eastern Pacific fishes are cited in the body of the text, or were referred to in Ahlstrom (1971).

NUMBER OF FISH LARVAE OBTAINED ON EASTROPAC II

Fish larvae were obtained in all collections (355) made with the 1-m plankton net on ETP II; counts of larvae per haul ranged from 1 to 2,864, and averaged 347. Four collections contained 10 or fewer larvae, and 22 collections contained 1,000 or more specimens in each (Table 6).

Abundance of fish larvae according to latitude and proximity to shore within the EASTROPAC pattern is summarized in Table 7. The same grouping of stations by latitude (5° except near the equator) and longitude (inshore-offshore) is used as in Table 4 (temperature summary

table). Subtotals provide a rough separation into quadrants.

Larvae were taken in greatest abundance in the northeast quadrant, particularly between lat 5° and 10°N; in this latter area, with an average surface temperature of 27.1°C, larvae averaged 639 per haul. Larvae were less abundant in the southeast quadrant, with numbers decreasing southward and averaging only 118 larvae per haul between lat 10° and 15°S (average surface temperature, 18.1°C).

Larvae were much less abundant offshore, in the northwest quadrant, averaging slightly over 40% as many per haul as in the inshore (northeast) quadrant. Surface temperatures, however, were quite similar.

Near the equator (lat 2°N to 2°S), larvae were moderately abundant inshore (434 per haul), and the decrease in the abundance offshore was not as marked as in other areas (362 per haul). This is not surprising, since this was an area of upwelling.

In the southwest quadrant (lat 2° to 10°S, long 110° to 119°W), there was a decrease in abundance toward the south. However, this quadrant was poorly sampled on ETP II. When compared to inshore coverage of the same latitude (lat 2° to 10°S), abundance of larvae per haul averaged about 62% as many.

Fish larvae averaged more per haul on ETP II as compared with comparable coverage on ETP I, 347.0 versus 231.9 larvae per haul; the increase in abundance was reflected in all parts of the EASTROPAC pattern.

The majority of large collections of fish larvae were made at stations with shallow thermoclines and relatively high mixed layer water

TABLE 6.—Relative numbers of fish larvae obtained over the three vessel patterns occupied on EASTROPAC II; last column gives comparable counts for EASTROPAC I.

No. of fish larvae per haul	Washington 45,000 Series	Undaunted 46,000 Series	Rockaway 47,000 Series	All patterns — EASTROPAC II	Comparable Coverage — EASTROPAC I
0	0	0	0	0	4
1-10	1	0	3	4	6
11-100	29	16	27	72	122
101-1,000	78	72	107	257	214
1,001 and over	3	7	12	22	9
Total	111	95	149	355	355
Average no. larvae per haul	224.0	400.3	404.7	347.0	231.9

TABLE 7.—Total catches of fish larvae (actual counts) taken on EASTROPAC II summarized by latitude (5° except near equator) and longitude (offshore or inshore).

Latitude	Offshore: long 100°-119°W			Inshore: coast to long 98°W		
	Number stations occupied	Number of larvae per haul		Number stations occupied	Number of larvae per haul	
		Range	Mean		Range	Mean
15°-20°N	32	31-1,048	219.0	1	130	130.0
10°-15°N	30	58- 481	159.1	23	37-2,242	435.4
5°-10°N	21	21-1,128	237.4	42	61-2,864	639.1
2°-5°N	16	93-1,217	359.6	28	141-1,975	555.1
Total 2°-20°N	99	21-1,128	227.5	94	37-2,864	558.8
Equator 2°N-2°S	21	30-1,506	361.5	30	1-1,513	434.4
2°- 5°S	14	79- 817	268.5	20	6-1,061	431.4
5°-10°S	16	8- 472	178.2	30	27-1,002	287.3
10°-15°S	--	--	--	31	4- 579	118.0
Total 2°-15°S	30	8- 817	220.4	81	4-1,061	258.1
Grand total	150	8-1,506	244.8	205	1-2,864	421.8

temperatures. Over 60% of the larger collections of fish larvae (750 or more larvae) were taken at stations with mixed layer temperatures in excess of 26°C and mixed layer depths of 35 m or less.

Unfortunately, information is lacking on the depth distribution of fish larvae in the eastern tropical Pacific in relation to thermocline depth, hence it is not known whether most kinds were limited in depth distribution to the upper mixed layer, as reported for California Current waters (Ahlstrom, 1959).

KINDS OF FISH LARVAE OBTAINED ON EASTROPAC II

With some interesting exceptions, the same kinds of larvae were obtained on ETP II as on ETP I, and Table 8, the principal summary table covering ETP II larvae, contains essentially the same families as its counterpart for ETP I. The table lists 53 families and 6 composite categories including 3 orders or suborders and a catchall category—other identified. For the latter, composition by families is given in subsequent tables or in text discussions. Altogether, fish larvae of 82 families were represented in ETP II collections. As on ETP I, larvae of 10 families contributed over 90% (91.0 on ETP II) of the total; 9 of these families were among the first 10 on both EASTROPAC surveys and had similar rankings. The first 10 families on ETP II

were as follows: Myctophidae, 52.0%; Gonostomatidae, 19.7%; Sternoptychidae, 6.0%; Bathylagidae, 4.8%; Bregmacerotidae, 2.5%; Paralepididae, 2.0%; Nomeidae, 1.2%; Melamphaidae, 1.1%; Engraulidae, 1.1%; and Idiacanthidae, 0.6%. Engraulidae is the only family on this list that did not rank among the first 10 on ETP I. The sole displacement from the previous list is the family Scombridae, which slipped in ranking from fifth in ETP I to twentieth in ETP II. Of the remaining 9%, 2.3% were too damaged (disintegrated) to identify, 0.7% could not be identified (these were mostly very small larvae), and the remainder, about 6%, belonged to the other 72 families.

The displacement of Scombridae from among the 10 most abundant families on ETP II left only one perciform family, Nomeidae, among those contributing 1% or more of the total. Only a moderate number of perciform families have become widely distributed in offshore oceanic waters. Among these, larvae of Gempylidae contributed 0.3% of the total on ETP II; Apogonidae, 0.2%; Chiasmodontidae, 0.2%; Coryphaenidae, 0.1%; Trichiuridae, 0.1%; and Bramidae, 0.1%.

The basic data on the kinds and number of fish larvae obtained in the 355 ETP II collections are contained in Appendix Tables 1 to 6. These are keyed to Table 8 and to other tables in this report.

The data presented in this paper represent but the first step in utilizing eggs and larvae collections for resource evaluation.

TABLE 8.—Occurrences and counts of fish larvae taken in oblique 1.0-m plankton hauls on the second multivessel EASTROPAC survey (EASTROPAC II), summarized by family or larger grouping and by research vessel.

Family or larger grouping ¹	Basic station data contained in Appendix Table no.		Distribution shown in Figure no.	Washington 45,000 Series		Undaunted 46,000 Series		Rockaway 47,000 Series		Total EASTROPAC II	
	By family or larger grouping	By genus or species		No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae
*1 Albulidae		4		0	0	0	0	2	9	2	9
*2 Clupeidae		4	3	0	0	7	185	2	85	9	270
*3 Engraulidae		4	3	4	15	2	3	29	1,342	35	1,360
*4 Argentinidae		3		14	21	14	32	4	5	32	58
*5 Bathylagidae	1	3	4	74	352	90	1,277	134	4,262	298	5,891
*6 Gonostomatidae	1	3	5-7	108	9,079	94	7,095	140	8,081	342	24,255
*7 Sternoptychidae	1			75	1,882	74	1,941	128	3,562	277	7,385
*8 Astronesthidae	3		5	10	16	15	30	17	28	42	74
*9 Chauliodontidae	1		8	10	25	10	15	36	167	56	207
*10 Idiacanthidae	1		9	49	275	62	219	70	301	181	795
*11 Other Stomiatoidei	1	3		60	245	64	219	86	570	210	1,034
12 Chlorophthalmidae				0	0	3	5	1	3	4	8
*13 Evermannellidae	3		10	9	47	7	19	1	1	17	67
*14 Myctophidae	1	2	3, 8, 11-14	111	9,546	95	21,082	146	33,381	352	64,009
15 Neoscopelidae				5	5	2	3	5	7	12	15
*16 Paralepididae	1	3		91	497	80	1,002	76	1,036	247	2,535
*17 Scopelarchidae	1			39	103	45	92	50	103	134	298
*18 Scopelosauridae	3		10	0	0	11	46	29	344	40	390
*19 Synodontidae	4		5	1	1	2	6	11	53	14	60
20 Alepisauridae				1	1	1	2	2	2	4	5
*21 Anguilliformes	5		14, 15	16	33	30	42	39	76	81	151
*22 Melamphidae	1		16	79	262	83	408	122	695	284	1,365
*23 Trachichthyidae	3			0	0	0	0	11	70	11	70
24 Holocentridae				3	10	0	0	0	0	3	10
*25 Bregmaceroideae	1			63	379	47	1,624	50	1,059	160	3,062
26 Macrouridae				1	1	3	3	5	5	9	9
*27 Scomberesocidae	3		14	0	0	0	0	27	153	27	153
28 Exocoetidae	1			15	26	22	33	22	87	59	146
29 Trachypteridae	1			10	10	16	20	20	29	46	59
*30 Apogonidae	1			29	178	24	73	14	32	66	283
31 Balistidae	3			1	1	3	6	1	1	5	8
32 Blenniidae				0	0	0	0	5	6	5	6
33 Bramidae	1			21	31	17	24	29	41	67	96
*34 Carangidae	4		17	8	28	8	59	20	137	36	224
35 Carapidae	4			0	0	0	0	7	7	7	7
36 Chiasmodontidae	1			25	46	25	45	50	146	100	237
*37 Coryphaenidae	1			37	56	34	62	38	67	109	185
*38 Gempylidae		3	4	35	59	30	64	46	247	112	370
*39 Gobiidae	4			5	65	11	33	37	286	53	384
40 Labridae	4		10	9	21	9	10	14	26	32	57
41 Mugilidae	4			0	0	0	0	5	16	5	16
*42 Nomeidae	1			68	357	64	391	97	712	229	1,460
*43 Ophidiidae				0	0	7	9	31	72	38	81
44 Polynemidae	4			2	21	2	5	3	5	7	31
45 Pomacentridae	4			1	6	0	0	4	5	9	11
46 Scaenidae	4			0	0	2	93	8	34	10	127
*47 Scombridae	1			15	70	24	89	16	89	53	248
48 Scorpaenidae	4			5	18	16	93	37	133	58	244
49 Serranidae	4			3	13	6	13	17	54	26	80
50 Sphyracnidae				0	0	1	2	1	8	2	10
*51 Tetragonuridae ²		3	17	5	5	5	6	1	1	11	12
*52 Trichiuridae		3	4, 17	3	3	2	2	44	181	49	186
*53 Bothidae		4	8	7	19	28	307	39	364	70	690
*54 Cynoglossidae		4		2	5	16	109	38	248	56	362
55 Ostraciontidae	3			14	49	1	1	0	0	15	50
*56 Lophiiformes	6		18	25	42	33	56	56	145	114	243
*57 Other identified				7	11	3	3	13	37	23	51
58 Unidentified larvae	1			48	171	56	265	78	426	182	862
59 Disintegrated larvae	1			96	753	77	809	115	1,252	288	2,814
Total				111	24,859	95	38,032	149	60,294	359	123,185

¹ Categories preceded by an asterisk are discussed in the text.

² Discussed in text under 42, Nomeidae.

TABLE 9.—Standardized counts of fish larvae compared with unstandardized (original) counts, summarized for selected families (see Appendix Table 8 for standardized haul factors).

Family or larger grouping	Standardized counts					Unstandardized counts	
	45,000 series	46,000 series	47,000 series	Total standardized counts	Percentage of total	Total unstandardized counts	Percentage of total
Bathylagidae	1,132	3,569	14,427	19,128	4.8	5,891	4.8
Gonostomatidae	31,525	19,347	26,717	77,589	19.5	24,255	19.7
Sternoptychidae	6,529	5,977	12,321	24,827	6.3	7,385	6.0
Chauliodontidae	97	43	589	729	0.2	207	0.2
Idiacanthidae	901	699	996	2,596	0.7	795	0.6
Other Stomiatoidei	914	732	2,061	3,707	0.9	1,107	0.9
Myctophidae	31,015	62,775	111,787	205,577	51.8	64,009	52.0
Paralepididae	1,712	2,724	3,511	7,947	2.0	2,535	2.1
Scopelarchidae	350	281	342	973	0.2	298	0.2
Melamphidae	818	1,227	2,223	4,268	1.1	1,365	1.1
Bregmacerotidae	1,259	5,772	3,210	10,241	2.6	3,062	2.5
Exocoetidae	78	104	245	427	0.1	146	0.1
Trachypteridae	32	63	93	188	<0.1	59	<0.1
Apogonidae	636	228	110	974	0.2	283	0.2
Bramidae	99	77	138	314	0.1	96	0.1
Chiasmodontidae	161	123	501	785	0.2	237	0.2
Coryphaenidae	185	194	227	606	0.2	185	0.2
Nomeidae	1,132	1,235	2,345	4,712	1.2	1,460	1.2
Scombridae	237	296	284	817	0.2	248	0.2
Other identified	1,704	3,893	13,204	18,801	4.7	5,886	4.8
Unidentified	590	827	1,274	2,691	0.7	862	0.7
Disintegrated larvae	2,604	2,405	4,255	9,264	2.3	2,814	2.3
Total fish larvae	83,710	112,591	200,860	397,161	100.0	123,185	100.1

Relative abundance of fish as larvae is not necessarily proportional to their relative abundance as adults. A number of parameters would have to be evaluated if counts of eggs and larvae of a species are to be used in determining the biomass of adult populations. These include fecundity (preferably given as number of eggs spawned in relation to fish weight—such as number of eggs spawned per gram of female weight); egg size, which influences size and state of development at hatching; duration of time spent in plankton both as egg stage and as larva as related to temperature of development; mortality rates during embryonic and larval stages; size at transformation; length of spawning season; age structure of population; etc.

I am assuming that the relative abundances of larvae of a given species are comparable from cruise to cruise in the EASTROPAC area. I am further assuming that comparisons of relative abundance within a family, as for example among myctophid or among scombrid larvae, will reflect their relative abundance as adults within reasonable limits. I, however, would caution against taking comparisons between families too literally until essential parameters are evaluated for each.

Actual counts of larvae rather than standardized values are used in tabulations throughout the paper, except Table 9. Table 9 compares summations of larvae of selected families based on standardized values with summations based on actual counts. These families make similar percentage contributions to the larval catch whether based on standardized counts or actual counts.

COMPARISON OF COMPOSITION AND RELATIVE ABUNDANCE OF LARVAE IN EASTROPAC II AND EASTROPAC I COLLECTIONS

In order to keep comparisons between the two EASTROPAC multivessel cruises completely relevant, the following stations lacking counterparts in ETP II were omitted from ETP I summations: Stations 11.146 to 11.328 of the outer pattern occupied by *Argo*, Stations 12.122 to 12.164 of the adjacent pattern occupied by *David Starr Jordan*, and Stations 13.095 to 13.155 of the next to inner pattern occupied by *Rockaway*. The remaining stations, by happy coincidence, total 355, are identical to the

TABLE 10.—Comparison of occurrences and relative abundance of fish larvae on EAS-TROPAC II (355 stations) with comparable coverage on EASTROPAC I (355 stations) summarized by family or larger grouping.

Family or larger grouping	EASTROPAC II			EASTROPAC I		
	No. positive hauls	No. larvae	Average no. per haul	No. positive hauls	No. larvae	Average no. per haul
Clupeidae	9	270	0.8	10	81	0.2
Engraulidae	35	1,360	3.8	10	205	0.6
Argentinidae	32	58	0.2	38	81	0.2
Bathylagidae	298	5,891	16.6	275	4,742	13.4
Gonostomatidae	342	24,255	68.3	333	18,380	51.8
Sternoptychidae	277	7,385	20.8	240	4,923	13.9
Astronesthidae	42	74	0.2	11	12	<0.1
Chauliodontidae	56	207	0.6	59	124	0.3
Idiacanthidae	181	795	2.2	132	855	2.4
Other Stomiatoidei	210	1,034	2.9	157	428	1.2
Chlorophthalmidae	4	8	<0.1	1	4	<0.1
Evermannellidae	17	67	0.2	10	13	<0.1
Myctophidae	352	64,009	180.3	346	39,249	110.6
Paralepididae	247	2,535	7.1	218	1,456	4.1
Scopelarchidae	134	298	0.8	109	273	0.8
Scopelosauridae	40	390	1.1	6	13	<0.1
Synodontidae	14	60	0.2	10	41	0.1
Anguilliformes	81	151	0.4	66	138	0.4
Melamphalidae	284	1,365	3.8	235	703	2.0
Trachypteridae	11	70	0.2	0	0	0
Bregmacerotidae	160	3,062	8.6	132	1,587	4.5
Scomberesocidae	27	153	0.4	1	1	<0.1
Exocoetidae	59	146	0.4	66	164	0.5
Trachypteridae	46	59	0.2	33	35	0.1
Apogonidae	66	283	0.8	37	135	0.4
Balistidae	5	8	<0.1	2	3	<0.1
Bramidae	67	96	0.3	40	49	0.1
Carangidae	36	224	0.6	31	183	0.5
Carapidae	7	7	<0.1	3	3	<0.1
Chiasmodontidae	100	237	0.7	48	97	0.3
Coryphaenidae	109	185	0.5	67	97	0.3
Gempylidae	112	370	1.0	59	110	0.3
Gobiidae	53	384	1.1	60	530	1.5
Labridae	32	57	0.2	28	40	0.1
Mugilidae	5	16	<0.1	5	9	<0.1
Nomeidae	229	1,460	4.1	159	900	2.5
Polynemidae	7	31	0.1	5	11	<0.1
Sciaenidae	10	127	0.4	4	12	<0.1
Scombridae	55	248	0.7	163	1,840	5.2
Scorpaenidae	58	244	0.7	47	162	0.5
Serranidae	26	80	0.2	26	252	0.7
Sphyrnaeidae	2	10	<0.1	3	3	<0.1
Tetragonuridae	11	12	<0.1	2	3	<0.1
Trichiuridae	49	186	0.5	19	48	0.1
Bothidae	70	690	1.9	56	199	0.6
Cynoglossidae	56	362	1.0	63	304	0.9
Lophiiformes	114	243	0.7	108	214	0.6
Other identified	76	247	0.7	--	159	0.4
Unidentified larvae	182	862	2.4	170	723	2.0
Disintegrated larvae	288	2,814	7.9	291	2,725	7.7
Total larvae	355	123,185	347.0	351 ¹	82,319	231.9

¹ Total stations 355 of which 351 contained larvae (positive hauls), 4 were negative.

count of stations occupied on ETP II. Hence, comparisons between the two cruises can be based on either the average number of larvae per haul or on "total numbers of larvae" of each category inasmuch as equal numbers of stations contributed to the totals.

Comparisons of occurrence and relative abundance of fish larvae in the ETP II pattern (all stations) with comparable coverage for ETP II are summarized by family or larger groupings in Table 10.

Nearly 50% more fish larvae were obtained per haul, on the average, in ETP II (347.0 larvae) as compared with ETP I (231.9 larvae). The larvae of most families of fishes were taken in larger numbers on ETP II than on ETP I, and larvae of several families were taken in markedly larger numbers. The striking exception to this trend was afforded by scombrid larvae; only 13.5% as many scombrid larvae were obtained in ETP II collections as in similar coverage of ETP I.

Families showing the largest increase in total numbers of larvae on ETP II compared with ETP I included Engraulidae (1,360 to 205 larvae), Scomberesocidae (153 to 1 specimen), Scopelosauridae (390 to 13 larvae), Evermannellidae (67 to 13 larvae), Astronesthidae (75 to 13 larvae), Trachichthyidae (70 to 0 larvae), Sciaenidae (127 to 12 larvae), Trichiuridae (186 to 48 larvae), Gempylidae (370 to 110 larvae), and Clupeidae (270 to 81 larvae). For the majority of these, the increase in relative abundance of larvae was most marked in the inner pattern occupied by *Rockaway*. The species compositions involved in these increases, when known, are discussed later under the respective families.

For the majority of families, however, the increase in abundance of larvae on ETP II was moderate, seldom as much as double; for a third of the families, counts of larvae were not much different during the two contrasting periods of the year; thus the similarity in abundance of larvae during the two periods is the striking feature of this comparison.

COMPARISON WITH EASTROPAC MONITORING CRUISES

The portion of the eastern tropical Pacific pattern that could be covered by a single research vessel on surveys averaging 45 days was occupied at bimonthly intervals on four monitoring cruises by *David Starr Jordan*. The cruises were numbered as follows: 20,000 series for the April-May 1967 monitoring cruise, 30,000 series for the June-July monitoring cruise, 50,000 for the October-November 1967 moni-

toring cruise, and 60,000 for the December 1967-January 1968 monitoring cruise. The monitoring pattern is shown superimposed on ETP II stations in Figure 2; it consisted of four station lines all ending at lat 3°S. The outer line along long 119°W extended from lat 20°N, the inner line along long 98°W, off the Mexican coast (ca. lat 17°N). The two middle lines along long 105° and 112°W were doglegs veering coastward from about lat 12° or 13°N—one line ending up off Manzanillo, Mexico, and the other off Acapulco, Mexico.

Coverage equivalent to the monitoring pattern was determined for ETP I and II. For ETP I the following stations were occupied: 11.022 to 11.118 (35), 12.002 to 12.109 (50), 12.209 to 12.264 (24), and 13.187 to 13.265 (28); total 137 stations. For ETP II comparable coverage was obtained from Stations 45.016 to 45.114 (41), 45.191 to 45.365 (37), 46.002 to 46.069 (36), and 46.079 to 46.132 (27); total 141 stations.

COMPARISON OF LARVAL COMPOSITION IN MONITORING PATTERN VERSUS LARGER EASTROPAC PATTERN

In Table 11 a comparison is made for both ETP I and ETP II of the average number of larvae per haul and percentage contribution of larvae of the more important fish families in the monitoring pattern as compared with the total pattern occupied on ETP II.

The correspondence between relative abundance and composition of larvae in the monitoring pattern as compared with the larger ETP pattern is closer for ETP I collections than ETP II. The average abundance of larvae in the monitoring pattern on ETP I was 92% as large as for the larger ETP I pattern (equivalent to the coverage obtained on ETP II). The more abundant kinds of larvae—myctophids, gonostomatids, and sternoptychids—had similar average abundances per haul and similar percentage contributions in the monitoring pattern as compared with the more extensive ETP I coverage. Of the remaining seven families used in this com-

TABLE 11.—Comparison of relative abundance of fish larvae (average number per haul) in the monitoring pattern as compared with the total pattern occupied on EASTROPAC II and equivalent EASTROPAC I for more abundant families.

Family	EASTROPAC II						EASTROPAC I					
	Monitoring pattern (141 hauls)			Total pattern (355 hauls)			Monitoring pattern (137 hauls)			Pattern equivalent to total EASTROPAC II (355 hauls)		
	Average no. per haul	%	Rank	Average no. per haul	%	Rank	Average no. per haul	%	Rank	Average no. per haul	%	Rank
Myctophidae	116.4	45.6	1	180.3	52.0	1	104.9	49.0	1	110.6	47.7	1
Gonostomatidae	77.9	30.5	2	68.3	19.7	2	48.6	22.7	2	51.8	22.3	2
Sternoptychidae	12.8	5.0	3	20.8	6.0	3	14.2	6.6	3	13.9	6.0	3
Bathylagidae	4.9	1.9	5	16.6	4.8	4	6.4	3.0	5	13.4	5.8	4
Bregmacerotidae	3.4	1.3	7	8.6	2.5	5	6.6	3.1	4	4.5	1.9	6
Paralepididae	8.2	3.2	4	7.1	2.0	6	4.8	2.3	6	4.1	1.8	7
Nomeidae	4.2	1.7	6	4.1	1.2	7	3.6	1.7	7	2.5	1.1	8
Melamphaidae	2.9	1.1	9	3.8	1.1	8	1.5	0.7	10	2.0	0.9	10
Idiacanthidae	3.0	1.2	8	2.2	0.6	10	2.8	1.3	8	2.4	1.0	9
Scombridae	0.6	0.2	10	0.7	0.2	ca. 20	2.4	1.1	9	5.2	2.2	5
Other	20.8	8.2		34.5	9.9		18.1	8.5		21.5	9.3	
Total	255.1	99.9		347.0	100.0		213.9	100.0		231.9	100.0	

parison, four were taken in somewhat higher numbers in the monitoring pattern and three in the more extensive ETP I coverage. Among the latter, less than half as many scombrid larvae were taken per haul in the smaller pattern as compared with the larger.

The average abundance of larvae in the monitoring pattern on ETP II was only 73.5% as many as for the total ETP II pattern. Larvae of three families were slightly more abundant in the monitoring pattern than in the total ETP II pattern, including Gonostomatidae, Paralepididae, and Idiacanthidae; larvae of Scombridae and Nomeidae were about equally abundant in the two patterns. Four families of fishes, however, including Myctophidae and Sternoptychidae, were less abundant in the monitoring pattern as compared with the total ETP II pattern. Caution has to be exercised in the applications made of data from the monitoring pattern alone.

TEMPORAL CHANGES IN ABUNDANCE IN MONITORING PATTERN

Data from six successive bimonthly coverages of the monitoring patterns are exceptionally useful for determining the annual reproductive cycles of fishes in tropical waters. Data on relative abundance (average number per haul) are summarized for the 10 most common families

in Table 12 and for selected genera and species in Table 13. The time period covered by each of the six surveys is indicated in these tables, and will be used for identifying cruises in the discussion.

The first thing to note is the range in abundance of total larvae on the six cruises: the highest abundance, 255.1 larvae per haul (August-September) was slightly less than double the lowest abundance, 133.1 larvae per haul in December-January. Range in abundance of larvae of each of the 10 families during the yearly cycle will be briefly discussed.

Myctophidae ranked first in all cruises, although barely so in the cruise made during June-July. The highest average number of larvae per haul, 116.4, obtained in August-September was almost double the lowest value, 58.7 larvae obtained in December-January. Myctophid larvae were as low as 37.9% of the total larvae (June-July), as high as 57.1% (October-November), and had an overall percentage contribution of 47.5%.

Gonostomatidae ranked second in all cruises; the lowest abundance per haul, 32.6 larvae in October-November, was less than half the highest value, 77.9 larvae per haul in August-September. Percentage contribution ranged between 18.5% (October-November) and 37.7% (June-July) and averaged 26.9%.

Sternoptychidae ranked third in abundance

TABLE 12.—Relative abundance and percentage contribution of fish larvae of the 10 most common families within that portion of EASTROPAC area covered on six successive bimonthly cruises between February 1967 and January 1968.

Family	ETP multivessel I ¹ (Feb.-Mar.)		ETP monitoring cruise #20 (Apr.-May)		ETP monitoring cruise #30 (June-July)		ETP multivessel II ² (Aug.-Sept.)		ETP monitoring cruise #50 (Oct.-Nov.)		ETP monitoring cruise #60 (Dec.-Jan.)		Six cruises - ETP monitoring area	
	Average no. per haul	%	Average no. per haul	%	Average no. per haul	%	Average no. per haul	%	Average no. per haul	%	Average no. per haul	%	Average no. per haul	%
Myctophidae	104.9	49.0	100.4	50.7	67.6	37.9	116.4	45.6	100.7	57.1	58.7	44.1	91.2	47.5
Gonostomatidae	48.6	22.7	50.6	25.6	67.3	37.7	77.9	30.5	32.6	18.5	33.7	25.3	51.6	26.9
Sternoptychidae	14.2	6.6	17.1	8.6	9.5	5.3	12.8	5.0	13.5	7.6	12.9	9.7	13.3	7.0
Bathylagidae	6.4	3.0	3.9	2.0	2.9	1.6	4.9	1.9	3.2	1.8	2.6	2.0	4.0	2.1
Paralepididae	4.8	2.3	4.1	2.1	5.3	3.0	8.2	3.2	3.2	1.8	4.8	3.6	5.1	2.7
Nomeidae	3.6	1.7	3.5	1.8	5.1	2.9	4.2	1.7	1.5	0.9	2.4	1.8	3.4	1.8
Bregmacerotidae	6.6	3.1	1.3	0.7	2.6	1.4	3.4	1.3	3.1	1.7	2.4	1.8	3.2	1.7
Idiacanthidae	2.8	1.3	2.9	1.5	2.0	1.1	3.0	1.2	1.1	0.6	1.5	1.1	2.2	1.1
Melamphaidae	1.5	0.7	1.8	0.9	1.6	0.9	2.9	1.1	1.7	1.0	1.3	1.0	1.8	0.9
Scombridae	2.4	1.1	1.4	0.7	1.0	0.6	0.6	0.2	1.3	0.8	1.4	1.1	1.4	0.7
Other	18.1	8.5	10.8	5.4	13.5	7.6	20.8	8.2	14.5	8.2	11.4	8.5	14.8	7.7
Total	213.9	100.0	197.8	100.0	178.4	100.0	255.1	99.9	176.4	100.0	133.1	100.0	192.0	100.1

¹ ETP I — stations 11.022-11.118 (35), 12.002-12.109 (50), 12.209-12.264 (24), and 13.187-13.265 (28).² ETP II — stations 45.016-45.114 (41), 45.191-45.365 (37), 46.002-46.069 (36), and 46.079-46.132 (27).

in all cruises. The average abundance per haul ranged from 9.5 larvae (June-July) to 17.1 (April-May), a range of less than two times.

Bathylagid smelts were represented in the monitoring pattern by a single species, *Bathylagus nigrigenys* Parr. Average abundance of larvae per haul ranged from 2.6 (December-January) to 6.4 (February-March) and averaged 4.0 larvae. Larvae of Bathylagidae usually ranked fifth in abundance.

Paralepididae usually ranked fourth in relative abundance; the lowest average abundance per haul was 3.2 larvae in October-November, and the highest was 8.2 larvae in August-September.

Nomeidae ranked variously fifth to eighth in relative abundance, with an overall ranking of sixth. The range in average abundance per haul was from 1.5 (October-November) to 5.1 larvae (June-July) and averaged 3.4 larvae.

Bregmacerotidae showed the widest variation in abundance, 1.3 larvae (April-May) to 6.6 larvae (February-March); consequently they ranked variously between fourth and tenth in relative abundance. Larvae of the most common species of *Bregmaceros* within the monitoring pattern, *B. bathymaster*, tend to cluster with occasional samples having rather large numbers of larvae. Variability in sampling due to chance encounters of clusters of larvae could be of

greater magnitude than that resulting from actual changes in reproductive activity during the year.

Idiacanthidae, usually ranked eighth in abundance per haul from 1.1 (October-November) to 2.9 larvae (April-May), with an overall average of 2.2 larvae per haul.

Melamphaidae ranked variously between seventh and tenth, with an overall rank of ninth. The lowest abundance, 1.3 larvae per haul in December-January, was less than half the highest, 2.9 larvae in August-September.

Scombridae in the monitoring area ranked either ninth or tenth in relative abundance of larvae on all cruises; the lowest average abundance, 0.6 larvae per haul in August-September, is only a fourth of the highest average value, 2.4 larvae in February-March.

Larvae of these 10 families made up over 92% of the fish larvae in the monitoring pattern. In all instances, larvae of all principal families were taken throughout the year. The spread between the highest and lowest abundance values for larvae of these principal families of fishes was usually less than three times, and for Myctophidae and Sternoptychidae, was less than double.

A similar seasonal pattern of abundance was observed for individual genera or species (Table 13). I found it helpful to arrange the 18 ge-

TABLE 13.—Relative abundance (average number per haul) of pelagic fish larvae of selected genera and species within that portion of EASTROPAC area covered on six successive bimonthly cruises between February 1967 and January 1968.

Genus or species	ETP multi-vessel I (Feb.-May)	ETP monitor cruise #20 (Apr.-May)	ETP monitor cruise #20 (June-July)	ETP multi-vessel I (Aug.-Sept.)	ETP monitor cruise #30 (Oct.-Nov.)	ETP monitor cruise #60 (Dec.-Jan.)	Range	Average six cruises
	6.4	3.9	2.9	4.9	3.2	2.6	2.6-6.4	4.0
<i>Bathylagus nigrigenys</i>	3.7	3.0	3.7	3.0	1.2	2.7	1.2-3.7	2.9
<i>Cyclothone</i> spp.	0.6	0.4	0.6	0.6	0.7	0.4	0.4-0.7	0.6
<i>Diplophos taenia</i>	43.3	45.8	62.5	71.9	30.3	30.0	30.0-71.9	47.3
<i>Vinciguerrria lucetia</i>	0.4	0.1	0.1	0.2	0.2	0.2	0.1-0.4	0.2
<i>Chauliodus</i> sp.	2.8	2.9	2.0	3.0	1.1	1.5	1.1-3.0	2.2
<i>Idiacanthus</i> sp.	0.9	0.6	0.6	1.3	0.6	0.9	0.6-1.3	0.8
<i>Bathophilus filifer</i>	51.1	63.0	37.4	68.6	62.2	31.8	31.8-68.6	52.4
<i>Diogenichthys laternatus</i>	0.7	0.8	0.3	0.7	0.5	0.2	0.2-0.8	0.5
<i>Goniichthys tenuiculus</i>	2.5	1.0	1.5	1.5	1.4	1.1	1.0-2.5	1.5
<i>Hygophum atratum</i>	3.0	2.7	2.0	2.7	3.0	1.1	1.1-3.0	2.4
<i>Hygophum proximum</i>	2.8	2.4	2.0	2.0	1.6	1.5	1.5-2.8	2.0
<i>Notolichthys valdiviae</i>	0.9	0.9	0.5	1.1	0.6	1.0	0.5-1.1	0.8
<i>Notoscopelus resplendens</i>	1.4	0.4	1.0	1.9	1.2	1.0	0.4-1.9	1.2
<i>Symbolophorus evermanni</i>	0.9	0.8	0.5	0.8	0.3	0.3	0.3-0.9	0.6
<i>Triphoturus</i> sp.	2.2	1.1	0.7	0.5	1.1	1.1	0.5-2.2	1.1
<i>Auxis</i> spp.	0.3	0.5	0.7	0.7	0.3	0.2	0.2-0.7	0.4
<i>Coryphaena</i> spp.	0.8	1.1	1.3	1.6	0.6	0.4	0.4-1.6	1.0
<i>Howella pammelas</i>	89.2	66.4	58.1	88.1	66.3	55.1	55.1-89.2	70.5
All others	213.9	197.8	178.4	255.1	176.4	133.1	133.1-255.1	192.4
Total								

nera and species of this table according to the magnitude of the seasonal change in abundance that each displayed.

Seasonal range in relative abundance between highest and lowest average number of larvae per haul:

Less than $2\times$: *Notolichthys valdiviae*

2.1 to $3\times$: *Bathylagus nigrigenys*, *Diplophos taenia*, *Vinciguerrria lucetia*, *Idiacanthus* sp., *Bathophilus filifer*, *Diogenichthys laternatus*, *Hygophum atratum*, *Hygophum proximum*, *Notoscopelus resplendens*, *Triphoturus* sp.

3.1 to $4\times$: *Cyclothone* spp., *Chauliodus* sp., *Goniichthys tenuiculus*, *Coryphaena* spp., *Howella pammelas*

4.1 to $5\times$: *Symbolophorus evermanni*, *Auxis* spp.

Larvae of the above 18 genera and species were taken on all cruises throughout the year. Obviously, reproduction is a continuous process for all of these, varying in amount at different seasons of the year and at different latitudes, but never stopping entirely.

Larvae of two species dominated the collections from the monitoring pattern: those of the myctophid *Diogenichthys laternatus* and of the gonostomatid, *Vinciguerrria lucetia*. Together these two species made up 44 to 56% of the total larvae in the monitoring pattern (Table 14).

The highest average abundance of larvae of the lanternfish, *Diogenichthys laternatus*, 68.6 larvae in August-September, was $2.5\times$ as much as the lowest average abundance, 31.8 larvae in December-January. Larvae of this species ranked first in abundance between October and May, but were less abundant than larvae of *Vinciguerrria lucetia* during June-September. Larvae of *Vinciguerrria lucetia* had a range of $2.4\times$ between their highest average abundance per haul, 71.9 larvae in August-September, and lowest, 30.0 larvae in December-January. A small but consistent change in abundance with season is evident for this species, with the peak period in June-September, the minimal period in October-January, and intermediate abundance of larvae in February-May.

The monitoring cruises were valuable in permitting us to establish the seasonal patterns of

TABLE 14.—Percentage contributions of larvae of the two most abundant species to the total catch of larvae in the monitoring pattern.

Cruise designation	Time of survey	Percentage contribution of larvae of		
		<i>Vinciguerria lucetia</i>	<i>Diogenichthys laternatus</i>	Combined
EASTROPAC I	Feb.-Mar.	20.2	23.9	44.1
20,000 series	Apr.-May	23.2	31.8	55.0
30,000 series	June-July	35.0	21.0	56.0
EASTROPAC II	Aug.-Sept.	28.6	26.9	55.1
50,000 series	Oct.-Nov.	17.2	35.3	52.5
60,000 series	Dec.-Jan.	22.5	23.9	46.4
	Annual	24.6	27.2	51.8

reproduction in oceanic, tropical fishes. Except for this, little more was gained from the repeated coverages that was not evident from any one of the six coverages. The same species composition was observed in all six cruises, and even the relative abundance of the various constituents did not change much. The similarity between cruises also extended to the geographic distributions of the various constituents which changed but little over time.

COMPARISON WITH RV OCEANOGRAPHER ZIG-TRANSECT

Although the average number of larvae per haul was almost identical for the *Oceanographer* collections and equivalent ETP II collections, 488.5 versus 487.8 larvae, and the kinds of larvae obtained were strikingly similar, the relative abundance of several categories was somewhat more variable than in the monitoring pattern (Table 15).

Similarities and differences in relative abundance of larvae during the two coverages can be shown from a consideration of the 10 families with highest abundance in the *Oceanographer* collections (Table 16).

Myctophidae.—The difference in relative abundance of *Myctophidae* larvae between *Oceanographer* and ETP II collections, 194.1 versus 273.9 larvae per haul, is almost entirely due to difference in relative abundance of larvae of *Diogenichthys laternatus*. Over 50% of *D. laternatus* larvae on ETP II were taken in four contiguous stations between lat 5°40' and 7°44'N, with three collections exceeding 1,000 larvae and the largest with 2,505 larvae. In-

terestingly, the two *Oceanographer* collections containing more than 1,000 *D. laternatus* larvae were taken between lat 6° and 7°N; these were the only two stations occupied between lat 5°40' and 7°44'N by *Oceanographer* in contrast to four collections from this rich area on ETP II.

Gonostomatidae.—The difference in relative abundance of *Gonostomatidae* larvae in the two occupancies of the zig-transect was again due principally to a single species, *Vinciguerria lucetia*. Although twice as many larvae of this species were taken in *Oceanographer* collections, an examination of the station record revealed that one collection, OP.036 with 2,046 larvae, accounted completely for the difference.

Clupeidae.—It is necessary to examine the species composition to evaluate differences between the two coverages (Table 17). Larvae of the sardine, *Sardinops sagax*, were taken in six contiguous stations near the Galapagos on ETP II, and averaged 29 larvae per positive haul, whereas only 1 sardine larva was obtained from the same area by *Oceanographer*. This species appears to have a period of peak spawning with reduced reproduction at other periods of the year. The contrast between the two collections of thread herring, *Opisthonema* sp., made at the station nearest the Mexican coast along long 92°W is the largest observed in EASTROPAC collections—2,730 larvae in the *Oceanographer* sample versus one larva in the ETP II collection. The larvae in the *Oceanographer* collection were intermediate-sized, 6 to 12.5 mm. Even allowing for the circumstance that clupeid larvae often occur in patches, this exceptionally large collection of larvae must have been obtained at a peak period of spawning of thread herring.

Bathylagidae.—Larvae of the two species of bathylagid smelts that occur in the area covered by the zig-transect, were similar in distribution and relative abundance in the two coverages. Larvae of *Bathylagus nigrigenys* were taken in all but three collections on each coverage, and average abundance per haul was almost identical, 26.3 versus 26.6 larvae (Table 17). Larvae of *Leuroglossus stilbius urotronus* had a more restricted distribution on both coverages, occurring between about 7°S and the equator, at sta-

TABLE 15.—Comparison of composition of catches of fish larvae in *Oceanographer* zig-transect, occupied in November-December 1967, with equivalent coverage by EASTROPAC II vessels during August-September 1967.

Family or larger grouping	<i>Oceanographer</i> (50 stations)			Equivalent ETP II coverage (48 stations)		
	No. positive hauls	No. larvae	Average no. per haul	No. positive hauls	No. larvae	Average no. per haul
Clupeidae	2	2,737	54.7	7	185	3.9
Engraulidae	6	760	15.2	15	381	7.9
Argentinidae	0	0	0	2	2	<0.1
Bathylagidae	47	2,308	46.2	45	2,005	41.8
Gonostomatidae	47	4,386	87.7	45	2,386	49.7
Sternoptychidae	39	976	19.5	40	1,093	22.8
Chauliodontidae	16	47	0.9	9	19	0.4
Idiacanthidae	15	27	0.5	28	58	1.2
Other stomiatoidel	28	209	4.2	32	274	5.7
Myctophidae	50	9,706	194.1	47	13,149	273.9
Paralepididae	28	556	11.1	25	320	6.7
Scopelarchidae	15	138	2.8	9	36	0.8
Scopelarsauridae	11	14	0.3	19	32	0.7
Synodontidae	1	3	0.1	3	7	0.1
Anguilliformes	10	18	0.4	16	23	0.5
Melamphaidae	43	243	4.9	40	274	5.7
Bregmacerotidae	1	470	9.4	9	1,455	30.3
Macrouridae	3	3	0.1	4	4	0.1
Exocoetidae	5	16	0.3	6	11	0.2
Scomberesocidae	1	1	<0.1	6	7	0.1
Trachypteridae	7	11	0.2	8	11	0.2
Apogonidae	1	1	<0.1	5	14	0.3
Bramidae	13	22	0.4	7	10	0.2
Carangidae	2	354	7.1	5	56	1.2
Chiasmodontidae	27	65	1.3	13	38	0.8
Coryphaenidae	8	8	0.2	8	13	0.3
Gempylidae	7	21	0.4	9	30	0.6
Gobiidae	6	42	0.8	12	35	0.7
Labridae	3	3	0.1	3	3	0.1
Nomeidae	37	185	3.7	27	155	3.2
Ophidiidae	6	10	0.2	5	6	0.1
Sciaenidae	4	34	0.7	4	96	2.0
Scombridae	7	82	1.6	10	41	0.9
Scorpaenidae	9	14	0.3	11	86	1.8
Serranidae	2	28	0.6	6	9	0.2
Sphyraenidae	1	1	<0.1	1	2	<0.1
Trichiuridae	4	4	0.1	8	10	0.2
Bothidae	14	67	1.3	17	227	4.7
Cynoglossidae	7	164	3.3	10	99	2.1
Lophiiformes	20	39	0.8	13	23	0.5
Other identified	6	104	2.1	12	23	0.5
Unknown larvae	21	53	1.1	21	100	2.1
Disintegrated larvae	42	488	9.8	42	606	12.6
Total larvae	50	24,417	488.5	48	23,414	487.8

tions occupied shoreward of the Galapagos Islands; the average abundance per haul was slightly higher in *Oceanographer* collections—19.9 versus 15.1 larvae.

Engraulidae—Larvae of *Engraulis ringens* were taken in more collections on ETP II (Table 17), but in lesser numbers per positive haul than in *Oceanographer* collections. The spawning period of the Peruvian anchovy is mostly between August and February (Einarsson and

Rojas de Mendiola, 1967); both coverages were within this period of the year. Larvae of other engraulids were taken at the inner station off Mexico in both coverages, but in markedly larger numbers by *Oceanographer*. Larvae of Sternoptychidae, Melamphaidae, and Paralepididae had similar frequency of occurrence in the two coverages (Table 16); differences in relative abundance were small to moderate.

Carangid larvae were taken in more collec-

TABLE 16.—Comparison of occurrence and average abundance per haul of larvae of 10 families with highest relative abundance on *Oceanographer* zig-transect with equivalent coverage on ETP II.

Family	<i>Oceanographer</i> (50 stations)			Equivalent ETP II (48 stations)		
	No. positive hauls	Average no. per haul	Rank	No. positive hauls	Average no. per haul	Rank
Myctophidae	50	194.1	1	47	273.9	1
Gonostomatidae	47	87.7	2	45	49.7	2
Clupeidae	2	54.7	3	7	3.9	11
Bathylagidae	47	46.2	4	45	41.8	3
Sternoptychidae	39	19.5	5	40	22.8	5
Engraulidae	6	15.2	6	15	7.9	6
Paralepididae	28	11.1	7	25	6.7	7
Bregmacerotidae	1	9.4	8	9	30.3	4
Carangidae	2	7.1	9	5	1.2	--
Melamphidae	43	4.9	10	40	5.7	8

tions on ETP II, 5 versus 2 (Table 16), but one of the two positive hauls at *Oceanographer* stations contained 353 larvae. This is considered a chance collection of a patch of larvae. Larvae of Bregmacerotidae were taken in only one *Oceanographer* collection, compared to nine on ETP II. Larvae of two species of *Bregmaceros* were represented in ETP II stations but only larvae of *B. bathymaster* were taken in large numbers. The single *Oceanographer* collection of 470 larvae of this species was made at the inner station off Mexico; two large collections of *B. bathymaster* larvae were made at the two inner stations off Mexico on ETP II (511 and 927 larvae). The principal difference in abundance of *Bregmaceros* larvae between the two coverages appears to be the chance collection of two patches versus one patch of *B. bathymaster* larvae.

I have gone into some detail in order to point up the influence of one or a few larger collections of larvae on the estimates of relative abundance (average number of larvae per haul) of several of the more abundant kinds of larvae in the zig-transect. Larvae of most kinds of fishes are patchily distributed, rather than randomly distributed. Variability associated with patchiness in distribution of larvae may be greater than variability due to temporal changes in reproductive activity. In this comparison, an example of temporal differences in reproductive activity is afforded by the sardine. The exceptionally large collection of thread herring

larvae is certainly indicative of very heavy spawning off Mexico in late November; the single larva taken in the same area on ETP II (September 15) may actually be indicative of low reproductive activity or, contrariwise, may simply reflect the circumstance that most hauls of patchily distributed species contain few or no larvae. Striking examples of the influence of one or a few collections on the estimates of abundance of larvae in the two coverages of the zig-transect are afforded by larvae of the two most common species, *Vinciguerria lucetia* (one collection) and *Diogenichthys laternatus* (two collections). I interpret difference in abundance of both species in the two time periods involved to be due primarily to variability associated with patchy distribution of larvae rather than to temporal differences in reproductive activity.

COMMENTS ON LARVAE OF THE MAJOR FISH FAMILIES COLLECTED ON EASTROPAC II

As mentioned in an earlier section, the kinds of larvae obtained on the second multivessel EASTROPAC cruise are summarized in Table 8 by family or larger grouping and by research vessel. This table contains 59 categories: 53 families and 6 composite categories including 3 orders or suborders and those labelled "other identified," "unidentified larvae," and "disintegrated larvae." Only those categories preceded by an asterisk are commented upon in the text discussion that follows; these include 31 families and 4 composite categories. Each category retains the sequential number given to it in this table.

The number of families included in the four composite categories are as follows: other Stomiatoidei (2), Anguilliformes (7), Lophiiformes (10), and "other identified" (10). Hence a total of 82 families were identified from ETP II collections.

Basic data on the kinds and numbers of fish larvae obtained in the 355 ETP II stations are contained in Appendix Tables 1-6, and station data including location, date and time of collection, depth of haul, and standardized haul factors for these stations are given in Appendix Table 8.

TABLE 17.—Comparison of composition of selected families and orders of fish larvae in *Oceanographer* zig-transect versus equivalent ETP II collections.

Categories	<i>Oceanographer</i> (50 stations)			Equivalent ETP II coverage (48 stations)		
	No. positive hauls	No. larvae	Average no. per haul	No. positive hauls	No. larvae	Average no. per haul
Clupeidae						
<i>Etrumeus acuminatus</i>	1	6	0.1	3	7	0.1
<i>Opisthonema</i> sp.	1	2,730	54.6	1	1	<0.1
<i>Sardinops sagax</i>	1	1	<0.1	6	177	3.7
Engraulidae						
<i>Engraulis ringens</i>	5	283	5.7	13	378	7.9
Other Engraulidae	1	477	9.5	2	3	0.1
Bathylagidae						
<i>Bathylagus nigrigenys</i>	47	1,315	26.3	45	1,278	26.6
<i>Leuroglossus stilbius urotronus</i>	13	993	19.9	12	727	15.1
Gonostomatidae						
<i>Cyclathone</i> spp.	26	90	1.8	24	75	1.6
<i>Ichthyococcus irregularis</i>	10	19	0.4	12	16	0.3
<i>Maurolicus muelleri</i>	16	177	3.5	12	282	5.9
<i>Vinciguerria lucetia</i>	47	4,085	81.7	45	2,000	41.7
Other Gonostomatidae	8	15	0.3	6	13	0.3
Myctophidae						
<i>Benthosema panamense</i>	1	43	0.9	2	88	1.8
<i>Diaphus</i> spp.	22	57	1.1	11	37	0.8
<i>Diogenichthys laternatus</i>	47	7,314	146.3	43	11,317	235.8
<i>Goniichthys tenuiculus</i>	24	63	1.3	16	52	1.1
<i>Hygophum atratum</i>	6	15	0.3	1	5	0.1
<i>Hygophum proximum</i>	2	2	<0.1	3	3	0.1
<i>Lampanyctus</i> spp.	49	1,041	20.8	38	610	12.7
<i>Myctophum aurolaternatum</i>	19	65	1.3	8	43	0.9
<i>Myctophum nitidulum</i>	27	445	8.9	24	314	6.5
<i>Notolychnus valdiviae</i>	9	24	0.5	10	71	1.5
<i>Notoscopelus resplendens</i>	24	75	1.5	10	80	1.7
<i>Protomyctophum</i> sp.	6	9	0.2	5	10	0.2
<i>Symbolophorus evermanni</i>	20	96	1.9	19	49	1.0
<i>Triphoturus</i> spp.	35	205	4.1	26	321	6.7
Other incl. unidentified myctophids	17	44	0.9	17	73	1.5
Disintegrated myctophids	32	208	4.2	21	76	1.6
Anguilliformes						
Congridae	2	3	0.1	2	3	0.1
Nemichthyidae	3	4	0.1	5	5	0.1
Nettastomidae	1	1	<0.1	0	0	0
Ophichthidae	5	8	0.2	7	11	0.2
Xenocongridae	0	0	0	1	1	<0.1
Family uncertain	2	2	<0.1	2	3	0.1
Lophiiformes						
Caulophrynidae	0	0	0	1	1	<0.1
Ceratiidae	3	3	0.1	1	2	<0.1
Gigantactinidae	1	1	<0.1	2	2	<0.1
Linophrynidae	5	8	0.2	3	3	0.1
Melanocoetidae	7	8	0.2	5	6	0.1
Oneirodidae	5	8	0.2	6	8	0.2
Lophiidae	1	1	<0.1	1	1	<0.1
Family uncertain	7	10	0.2	0	0	0

A summary of these tables follows.

Appendix Table 1.—Counts of fish larvae, tabulated by family, for all stations occupied on EASTROPAC II. This table contains 22 categories including 18 families, 1 suborder, and 3 composite categories for "other identified larvae," "unidentified larvae," and "disintegrated larvae." The latter category includes larvae too

damaged or disintegrated to identify with any certainty.

Appendix Table 2.—Counts of myctophid larvae, tabulated by genus or species, for all stations occupied on the second multivessel EASTROPAC cruise (ETP II). Myctophid larvae are tabulated by species for 13 kinds, by genus for 6 kinds, and 3 composite categories—"other

identified myctophids," "unidentified myctophids," and "disintegrated myctophids." A summary of this appendix table is contained in Table 19.

Appendix Table 3.—Counts of selected categories of fish larvae, tabulated by station, for all stations occupied on ETP II. Table contains 23 categories including 11 species, 5 genera, and 7 families. Of these, 12 were included in the category "other identified larvae" in Appendix Table 1, the remainder provide information on counts of larvae at the generic or specific level for several families listed in Appendix Table 1.

Appendix Table 4.—Summary of occurrences and numbers of larvae of 23 categories, limited in distribution to a broad coastal band or around offshore islands or banks. Only positive stations are included. These 23 categories were included under "other identified larvae" in Appendix Table 1.

Appendix Table 5.—Numbers and kinds of eel leptocephali (Anguilliformes) obtained on the second multivessel EASTROPAC cruise (ETP II), tabulated by family for all positive hauls. A summary of this table is given in Table 20.

Appendix Table 6.—Numbers and kinds of lophiiform larvae obtained on the second multivessel EASTROPAC cruise (ETP II) tabulated by family for all positive hauls. A summary of this table is given in Table 23.

Appendix Table 7.—7A contains counts of fish larvae, tabulated by family or larger grouping, for all stations occupied by *Oceanographer* on zig-transect; 7B contains station counts of myctophid larvae for same cruise, tabulated by genus or species; and 7C contains station counts of selected categories of fish larvae on same cruise.

Appendix Table 8.—Station data and standardized haul factors for second multivessel EASTROPAC cruise and for *Oceanographer* zig-transect. Included for each station are locality, date and time of collection, depth of haul, and standardized haul factor. The standardized haul factors are used to adjust original counts of larvae to the comparable standard of numbers of larvae in 10 m³ of water strained per meter of depth fished. It should be noted that the mid-time of haul for each station is recorded as Pa-

cific Standard Time. However, the symbols D (Daylight), N (Night), DT (Day Twilight), NT (Night Twilight) accurately reflect the local condition at each station. Twilight hauls were taken within 1 hr of local sunrise or sunset.

2. CLUPEIDAE

(9 occurrences, 270 larvae)

As on ETP I, three species of Clupeidae larvae were obtained. Larvae of the sardine, *Sardinops sagax* (Jenyns), (7 occurrences, 179 larvae) and round herring, *Etrumeus acuminatus* Gilbert, (3 occurrences, 7 larvae) were taken in the vicinity of the Galapagos Islands while larvae of the thread herring, *Opisthonema* sp., (2 occurrences, 84 larvae) were taken at two coastal stations off southern Mexico, with surface water temperatures of 28.7° and 29.3°C. Six of the occurrences of sardine larvae were at contiguous stations, along long 92°W, between lat 1°N and 3°S, just seaward of the Galapagos Islands (Figure 3). Surface water temperatures at these stations ranged between 16.4° and 19.3°C. We sampled the Galapagos sardine population on ETP II, at a period of rather high reproductive activity.

3. ENGRAULIDAE

(35 occurrences, 1,360 larvae)

The Peruvian anchovy, *Engraulis ringens* Jenyns, (25 occurrences, 1,307 larvae) also was sampled on ETP II during a period of high reproductive activity (Figure 3). Einarsson and Rojas de Mendiola (1967) determined that the spawning season of the Peruvian anchovy extended from August to March, hence the early part of the 1967-68 spawning season was sampled on ETP II and the close of the previous spawning season on ETP I. Surface temperatures at positive stations ranged between 15.4° and 18.8°C. Larvae of other engraulids (10 occurrences, 53 larvae) were taken at nearshore stations over a wide area between lat 20°N and the equator.

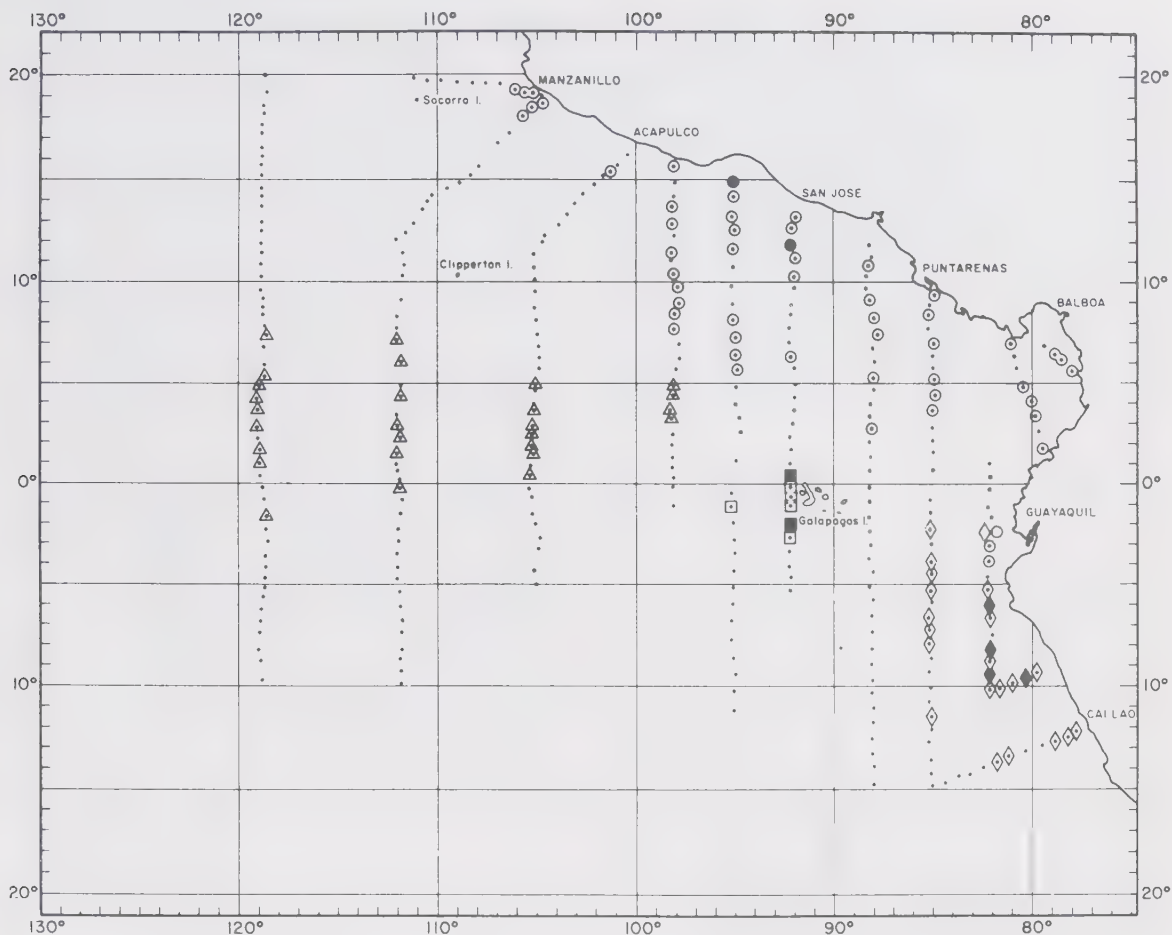


FIGURE 3.—Distribution of larvae of the clupeid, *Sardinops sagax* (open square with dot, 1-50 larvae; closed square, 51 or more larvae), of the engraulid, *Engraulis ringens* (open diamond with dot, 1-100 larvae; closed diamond, 101 or more larvae), of the myctophid, *Myctophum asperum* (open triangle with dot), and of the bothid flatfish, *Syacium ovale* (open circle with dot, 1-100 larvae; large solid circles, 101 or more larvae). Small solid circles represent other stations occupied on ETP II.

4. ARGENTINIDAE

(32 occurrences, 58 larvae)

In contrast to ETP I, from which three kinds of argentinid larvae were obtained, only one kind, *Nansenia* sp. A, was obtained on ETP II. Larvae of *Nansenia* were taken in an offshore equatorial band, between lat 8°N and 7°S. This distribution is closely similar to that illustrated for ETP I (Ahlstrom, 1971, Figure 2).

5. BATHYLAGIDAE

(298 occurrences, 5,891 larvae)

Larvae of two species of bathylagid smelts were taken on ETP II: *Bathylagus nigrigenys* Parr (293 occurrences, 3,787 larvae) and *Leuroglossus stilbius urotronus* (Bussing) (29 occurrences, 2,104 larvae).

In comparable coverage on ETP I, 2,852 larvae of *B. nigrigenys* were taken in 269 collections. The distribution of larvae on the two coverages was strikingly similar (Ahlstrom, 1971, Figure 3). On the two outer lines, occu-

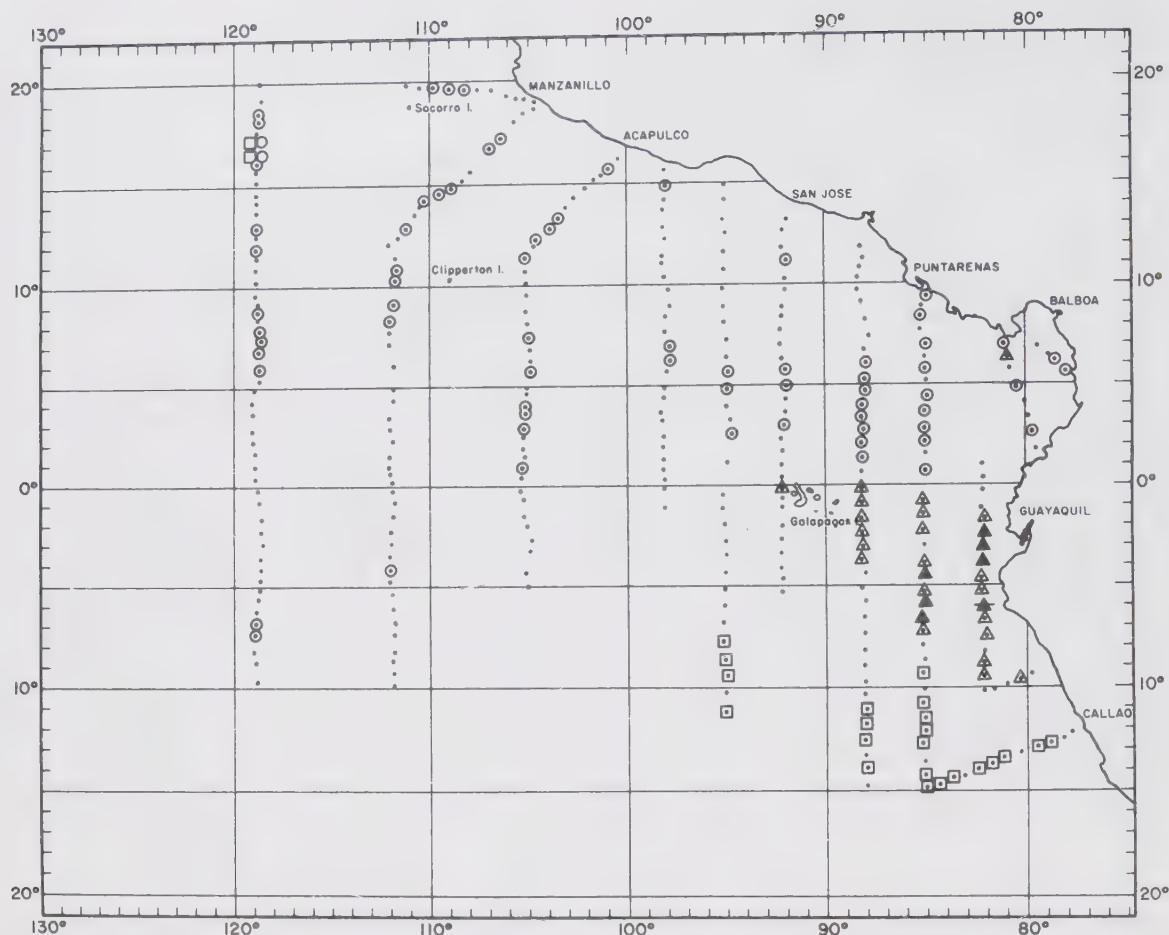


FIGURE 4.—Distribution of larvae of the bathylagid, *Leuroglossus stilbius urotranas* (open triangle with dot, 1-100 larvae; closed triangle, 101-500 larvae, and triangle with bisecting line, 501 or more), of the gempylid, *Gempylus serpens* (open circle with dot), and of the trichiurid, *Diplospinus multistriatus* (open square with dot). Small solid circles represent other stations occupied on ETP II.

pied by Washington, no larvae of *B. nigrigenys* were taken below ca. lat. 4°S. Absence of larvae of this species from the South Pacific central water mass was not as conclusively documented as on ETP I, primarily because of the paucity of coverage within the central water mass on ETP II. Counts of larvae exceeded 100 specimens per haul in five samples, taken between 0° and lat 3°S and long 85° to 92°W.

Larvae of *Leuroglossus stilbius urotranas* were taken in 29 collections; all but 2 of which were obtained in a compact area shoreward of the Galapagos Islands between 0° and lat 10°S

(Figure 4). The distribution of larvae of this species is one of the few that shows a striking contrast between ETP I and ETP II. On ETP I about half of the occurrences were to the north of the equator between 0° and lat 8°N (18 occurrences, 218 larvae—Ahlstrom, 1971, Figure 2), compared with only one occurrence, one larva in this area on ETP II. The distribution south of the equator was essentially similar on both surveys; on ETP I, 1,672 larvae were taken in 19 collections between 0° and lat 14°S, with the heaviest concentration of larvae in hauls taken between lat 3° and 6°S.

6. GONOSTOMATIDAE (342 occurrences, 24,255 larvae)

Gonostomatid larvae, exceeded in abundance only by myctophid larvae, were obtained in 97% of the ETP II collections and contributed 19.7% of the total fish larvae. The relative abundance and frequency of occurrences of larvae belonging to 10 genera of gonostomatids are summarized by vessel patterns in Table 18. The last two columns of this table give information concerning occurrence and relative abundance of gonostomatid larvae of the same genera for comparable coverage on ETP I.

Little change in abundance, distribution, or frequency of occurrence was shown by larvae of *Cyclothone* spp. and *Diplophos taenia* Günther, although both were slightly more abundant on ETP I. Average abundance of larvae of *Vinciguerria* spp. was about one-third greater than on equivalent ETP I, and almost three times as many larvae of *Maurollicus muelleri* (Gmelin) were obtained on ETP II. An interesting instance of a marked difference in seasonal abundance of larvae of a gonostomatid fish was found for larvae of *Yarrella argenteola* (Garman). Larvae of this species were taken in 17 collections on ETP II (Figure 6), whereas only one specimen was obtained on ETP I.

Araiophos eastropas Ahlstrom and Moser (1 occurrence, 35 larvae)

The single record on ETP II is from the southernmost station occupied by *Washington* on its outer line at lat 9°45'S, long 118°59'W. On ETP I, all occurrences of larvae of this species were taken between lat 10° and 18°S along long 119° and 126°W (Ahlstrom, 1971, Figure 4). Hence, it was exciting to obtain the single ETP II collection of larvae of *Araiophos* at the only station in the pattern that bordered on the distributional limits of this species as determined from ETP I collections.

Cyclothone spp. (187 occurrences, 972 larvae)

Larvae of *Cyclothone* spp. were taken in about an equal number of collections in the two surveys, 187 on ETP II versus 190 on equivalent coverage of ETP I, and in rather similar abundance—2.7 larvae per haul on ETP II as compared with 3.1 on equivalent ETP I. The distribution of larvae of *Cyclothone* on ETP II was similar to that illustrated for equivalent ETP I. As on ETP I, the fewest occurrences (19 of 68 collections) were obtained between lat 10° and 20°N, and the Peruvian coastal waters were almost as poor. However, *Cyclothone* larvae were more abundant in the portion of ETP I that was

TABLE 18.—Frequency of occurrence and relative abundance of the kinds of gonostomatid larvae on EASTROPAC II, and for equivalent coverage on EASTROPAC I.

Gonostomatid genera or species	Washington 45,000 series		Undaunted 46,000 series		Rockaway 47,000 series		EASTROPAC II total (355 hauls)		Equivalent EASTROPAC I total (355 hauls)	
	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae
<i>Araiophos eastropas</i>	1	35	0	0	0	0	1	35	0	0
<i>Cyclothone</i> spp.	64	358	54	331	69	283	187	972	190	1,106
<i>Danaphos oculatus</i>	1	1	0	0	0	0	1	1	0	0
<i>Diplophos taenia</i>	44	114	11	20	2	2	57	136	57	156
<i>Gonostoma</i> spp.	2	3	1	1	8	18	11	22	10	39
<i>Ichthyococcus</i> sp.	3	3	25	38	18	35	46	76	34	53
<i>Maurollicus muelleri</i>	4	11	24	551	19	211	47	773	43	264
<i>Vinciguerria</i> spp.	107	8,553	94	6,148	140	7,497	341	22,198	320	16,746
<i>Woodsia</i> sp.	0	0	2	3	2	2	4	5	3	3
<i>Yarrella argenteola</i>	0	0	1	1	17	32	18	33	1	1
Other gonostomatids	1	1	2	2	1	1	4	4	12	12
Total gonostomatids	108	9,079	94	7,095	140	8,081	342	24,255	330	18,380

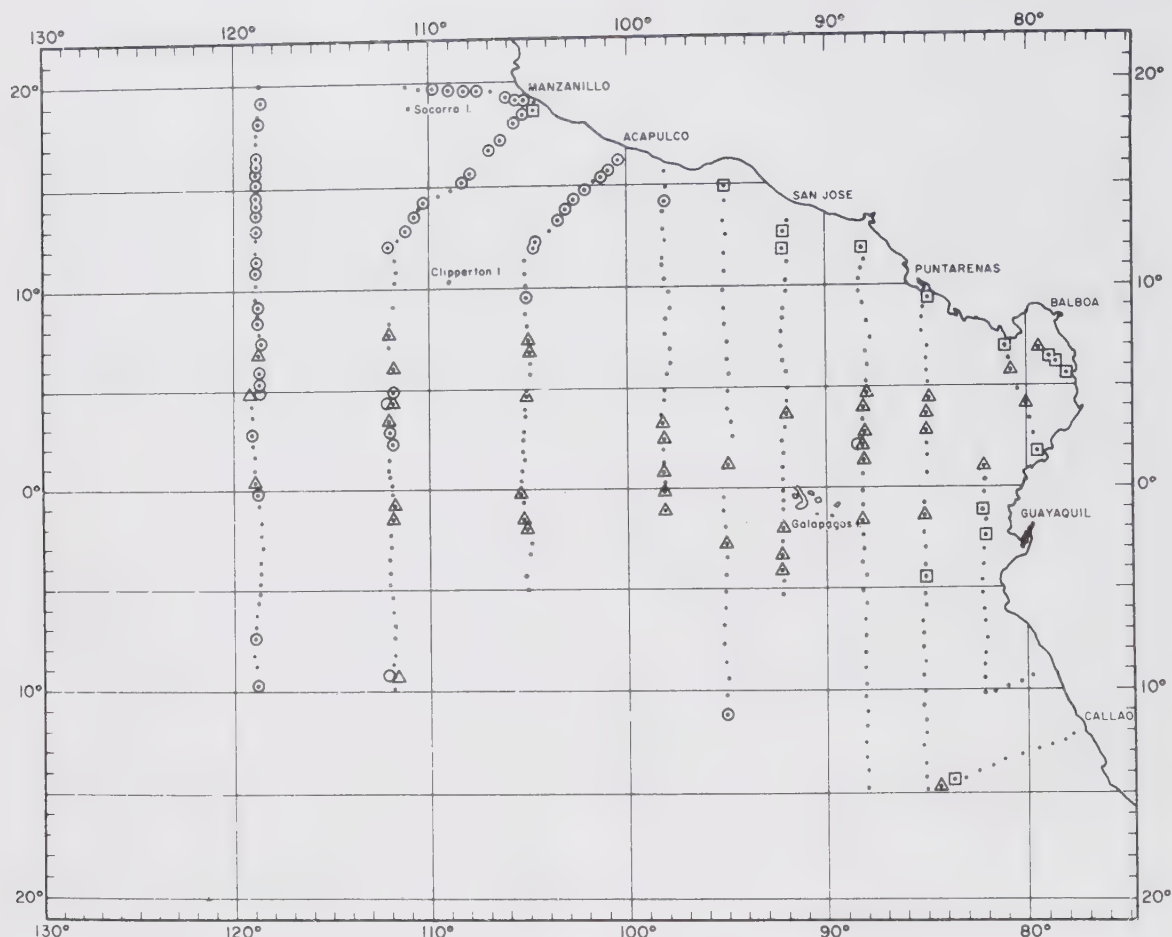


FIGURE 5.—Distribution of larvae of the gonostomatid, *Diplophos taenia* (open circle with dot), of the stomiatoid family, Astronesthidae (open triangle with dot), and of the synodontid genus, *Synodus* spp. (open square with dot). Small solid circles represent other stations occupied on ETP II.

not replicated on ETP II. In these collections *Cyclothone* larvae occurred in 111 of 127 collections, with an average abundance per collection of 8.7 larvae.

Danaphos oculatus (Garman)
(1 occurrence, 1 larva)

A single large larva was taken at the northern end of the *Washington* pattern at lat 19°16'N, long 118°56'W. Information obtained from California Current and NORPAC collections indi-

cates that *Danaphos* is a temperate water species, occurring most commonly in collections obtained from the central water mass of the North Pacific in hauls which sampled to depths greater than 140 m.

Diplophos taenia (Günther)
(57 occurrences, 136 larvae)

Larvae of *Diplophos taenia* afford a striking example of similarities in distribution, frequency of occurrences, and relative abundance in the

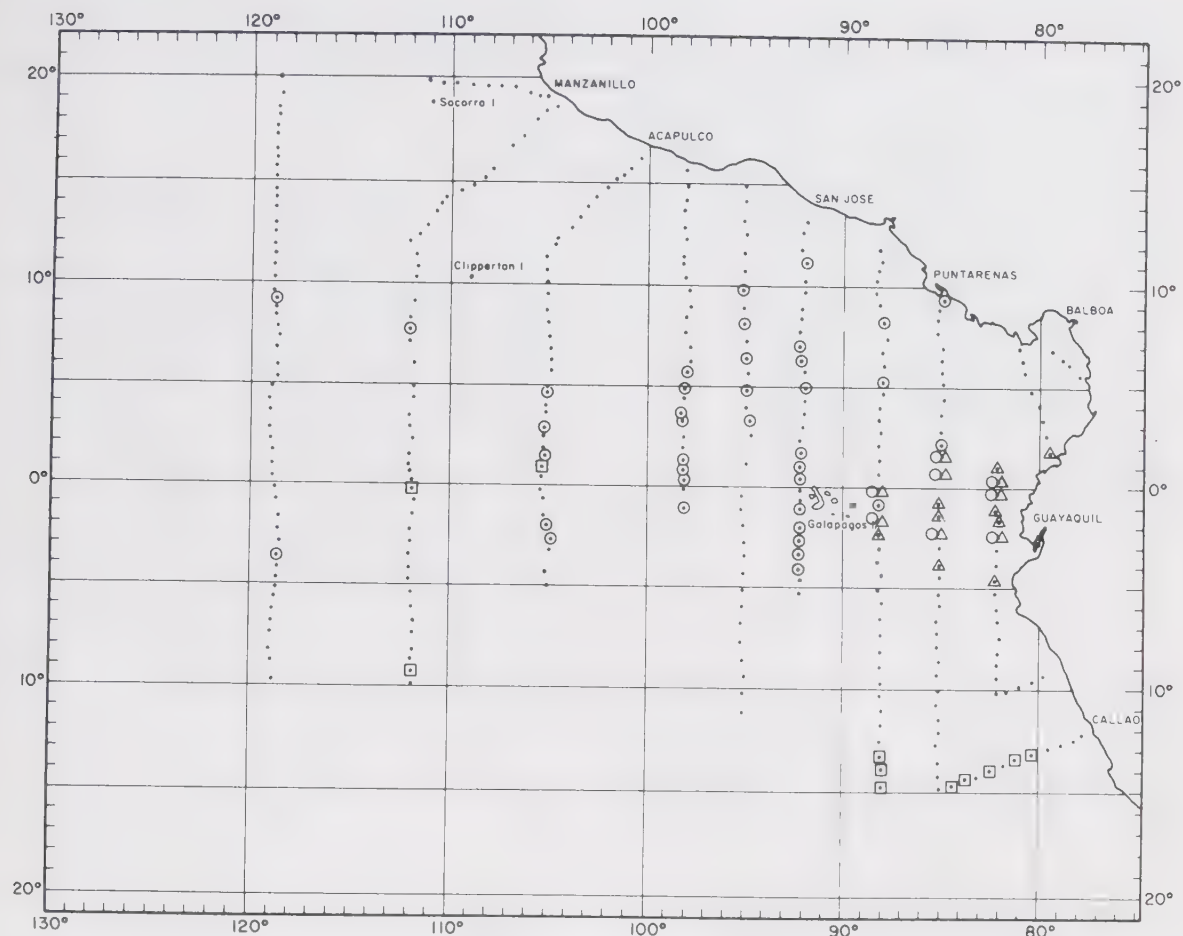


FIGURE 6.—Distribution of larvae of three kinds of gonostomatids. Records of occurrence of larvae of *Gonostoma* spp. shown as open square with dot, of *Ichthyococcus irregularis* as open circle with dot, and of *Yarella argenteola* as open triangle with dot. Small solid circles represent other stations occupied on ETP II.

two EASTROPAC multivessel cruises. Larvae were obtained in 57 collections from both ETP II and equivalent ETP I; on both surveys the majority of larvae were taken to the north of lat 10°N, particularly on the coastward-oriented portion of the station line terminating off Acapulco, Mexico, and that terminating off Manzanillo, Mexico (Figure 5, and Ahlstrom, 1971, Figure 4). Larvae of this species were taken in moderate numbers, seldom more than 5 per haul; the average number per haul on ETP II was 0.38 larva versus 0.44 larva on equivalent ETP I.

Gonostoma sp.

(11 occurrences, 22 larvae)

At least two kinds of gonostomatid larvae have been referred to *Gonostoma*, the more common being larvae of *G. elongatum* Günther. The distribution of *Gonostoma* larvae on ETP II is shown in Figure 6; 8 of 11 occurrences were in a compact group in the southern, inshore portion of the ETP pattern (between lat 13° and 15°S, offshore to long 88°W).

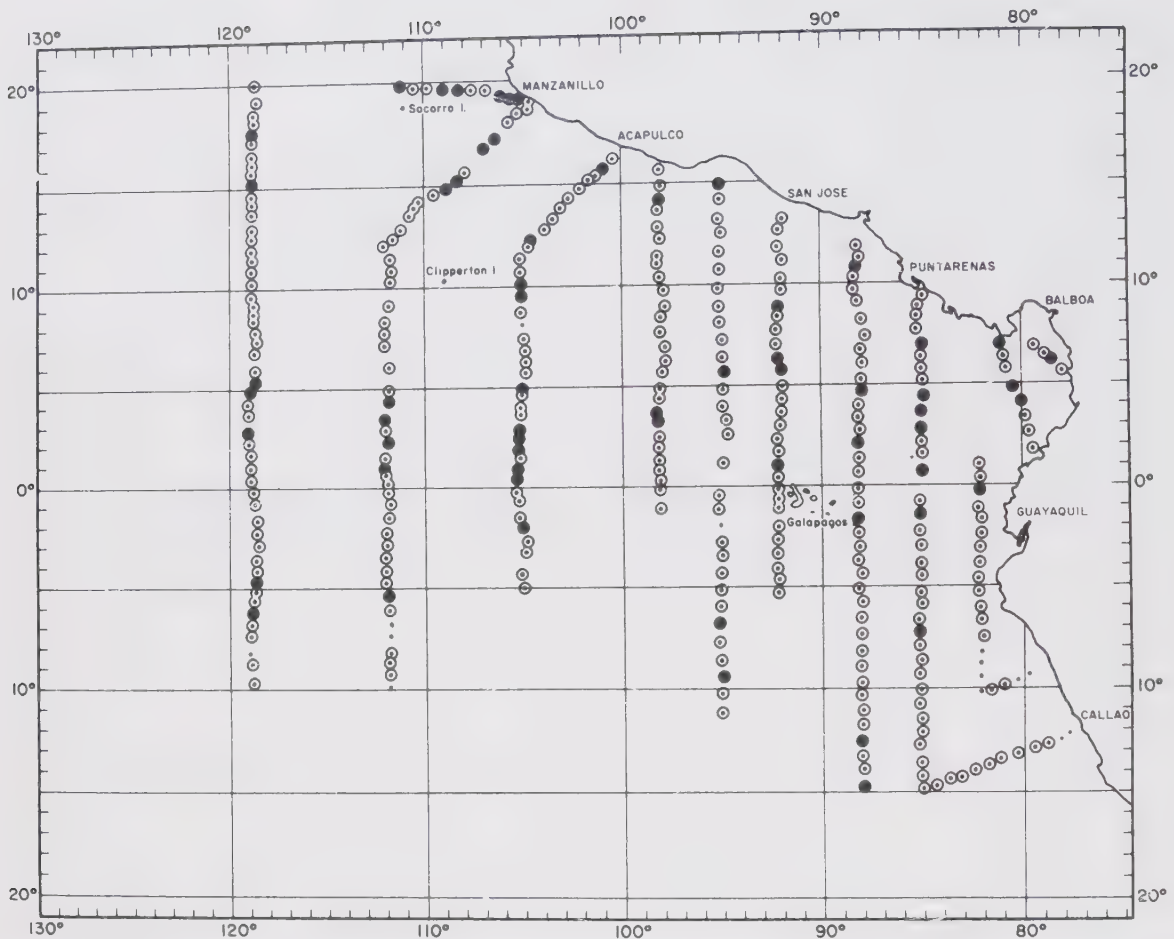


FIGURE 7.—Distribution of larvae of the gonostomatid, *Vinciguerrria* spp. on ETP II. Collections of 1-100 larvae are shown as open circles with dot in center, collections of 101 or more larvae as large solid circles; negative hauls are shown as small solid circles.

Ichthyococcus sp.

(46 occurrences, 76 larvae)

All *Ichthyococcus* larvae taken on ETP II were similar in appearance and have been referred to *I. irregularis* Rehnitz and Böhlke. Although widely distributed (Figure 6), all larvae were obtained between lat 12°N and 4°S; only three collections of *Ichthyococcus* larvae were taken in the outer pattern occupied by Washington.

Maurolicus muelleri (Gmelin)

(47 occurrences, 773 larvae)

Larvae of *M. muelleri* ranked third in abundance among gonostomatid larvae. As on ETP I, (Ahlstrom, 1971, Figure 4) larvae of this species were sampled in a rather narrow equatorial belt, and none were taken seaward of long 112°W. This again is a striking instance of the similarity in distribution of larvae on the two multivessel cruises. Although the incidence of occurrences of *Maurolicus* larvae was almost as

high in ETP I as in ETP II, 43 positive hauls as compared with 47, the average number of larvae per positive haul was much higher on ETP II—16.4 larvae versus 6.1 larvae.

Vinciguerria spp.

(341 occurrences, 22,198 larvae)

As in ETP I, larvae of *Vinciguerria* spp. ranked second in overall abundance, exceeded only by larvae of the myctophid, *Diogenichthys laternatus* (Garman). They were obtained throughout the EASTROPAC pattern, occurring in 96% of the collections (Figure 7). Average abundance of larvae per haul was about one-third greater than in ETP I: 62.5 versus 47.2 larvae.

Larvae of two species of *Vinciguerria* occur within the ETP II pattern, although most were those of *V. lucetia* Garman. As commented upon for ETP I, larvae of *V. nimbaria* (Jordan and Williamson) were taken principally in the South Pacific central water mass, to the south of about lat 5°S. On ETP II this distribution involves about 20 collections only.

Yarrella argenteola (Garman)

(18 occurrences, 33 larvae)

Larvae of *Y. argenteola* were taken in a limited area shoreward or immediately south of the Galapagos Islands between lat 2°N and 5°S (Figure 6). No metamorphosing specimens were observed, although larvae as large as 16 mm were represented in the collections. As noted in the introductory section, only one specimen of *Yarrella* was obtained on ETP I, in contrast to the 18 occurrences on ETP II. Adults of this species were recorded from within the area covered on ETP II by Morrow (1957b), Grey (1960), Bussing (1965), and Parin (1971).

7. STERNOPTYCHIDAE

(277 occurrences, 7,385 larvae)

As in ETP I, hatchetfish larvae ranked third in abundance. Although hatchetfish larvae con-

tributed almost identical percentages of the total larvae in ETP II as in comparable ETP I (5.99% versus 5.98%), the average number of larvae per haul, 20.8 versus 13.9, reflected the greater relative abundance of larvae on ETP II. As noted for ETP I, hatchetfish larvae are more fragile than most kinds, and a portion of the larvae are too damaged to identify, except to family. Even so, identification to genus was made for most ETP II collections, and in these, larvae of *Sternoptyx* sp. contributed about 85% of the total and larvae of *Argyropelecus* (mostly *A. lychnus* Garman), the remainder. Baird (1971) in his revision of the family Sternoptychidae recognized three species of *Sternoptyx*, with *S. obscura* Garman the common species in the eastern tropical Pacific; however, he included one record of *S. diaphana* Hermann from within the area surveyed on ETP II.

8. ASTRONESTHIDAE

(42 occurrences, 74 larvae)

Astronesthid larvae were taken in about four times as many collections as on equivalent ETP I. Most larvae had an equatorial distribution between lat 8°N and 5°S; only two larvae occurred elsewhere (Figure 5). Three distinctive kinds of astronesthid larvae were taken.

9. CHAULIODONTIDAE

(56 occurrences, 207 larvae)

Although larvae of *Chauliodus* sp. were taken in a comparable number of hauls on ETP II and ETP I (56 versus 59 occurrences), more larvae were obtained on ETP II (207 versus 134 larvae). The majority of *Chauliodus* larvae on ETP II were taken in the inner half of the ETP pattern, below the equator—34 collections containing 165 specimens were obtained from this quadrant (Figure 8). In other parts of the ETP pattern somewhat fewer larvae were taken than on ETP I. As on ETP I, the majority of positive hauls contained 1 to 3 larvae (41 of 56 hauls); even so, a higher proportion of the hauls on ETP II contained somewhat larger numbers of *Chauliodus* larvae, i.e., 6 to 26 larvae per haul.

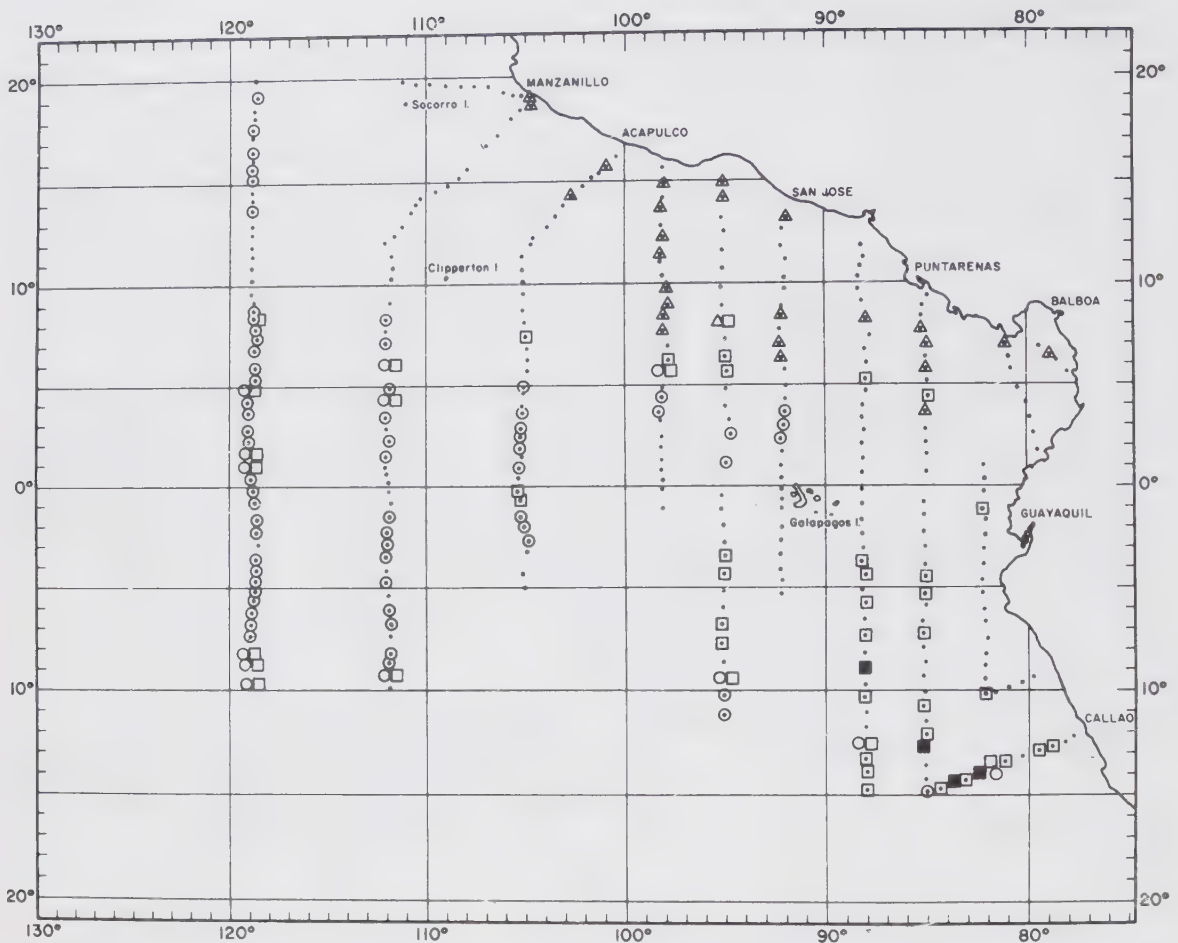


FIGURE 8.—Distribution of larvae of the stomiatoid genus *Chauliodus* sp. (open square with dot, 1-10 larvae, closed square, 11 or more larvae), of the myctophid, *Hygophum proximum* (open circle with dot), and of the bothid flatfish, *Bothus leopardinus* (open triangle with dot). Small solid circles represent other stations occupied on ETP II.

10. IDIACANTHIDAE (181 occurrences, 795 larvae)

Larvae of *Idiacanthus* sp. were taken in over half of the plankton hauls made on ETP II; there was an increase in frequency of occurrence of *Idiacanthus* larvae as compared to equivalent ETP I, but not in actual abundance of larvae. Larvae of *Idiacanthus* were most abundant in the inshore quadrant to the north of the equator and least abundant in the offshore quadrant south of the equator (Figure 9). All larger collections of larvae (11 to 43 larvae per haul)

were taken to the north of the equator, usually within 600 miles of the coast.

11. OTHER STOMIATOIDEI (210 occurrences, 1,034 larvae)

Included under other Stomiatoidei in Table 9 are larvae of two stomiatoid families: Stomiidae and Melanostomiidae. In Appendix Table 1, the category "other Stomiatoidei" also includes the family Astronesthidae. In Appendix Table 3, counts are given for three principal

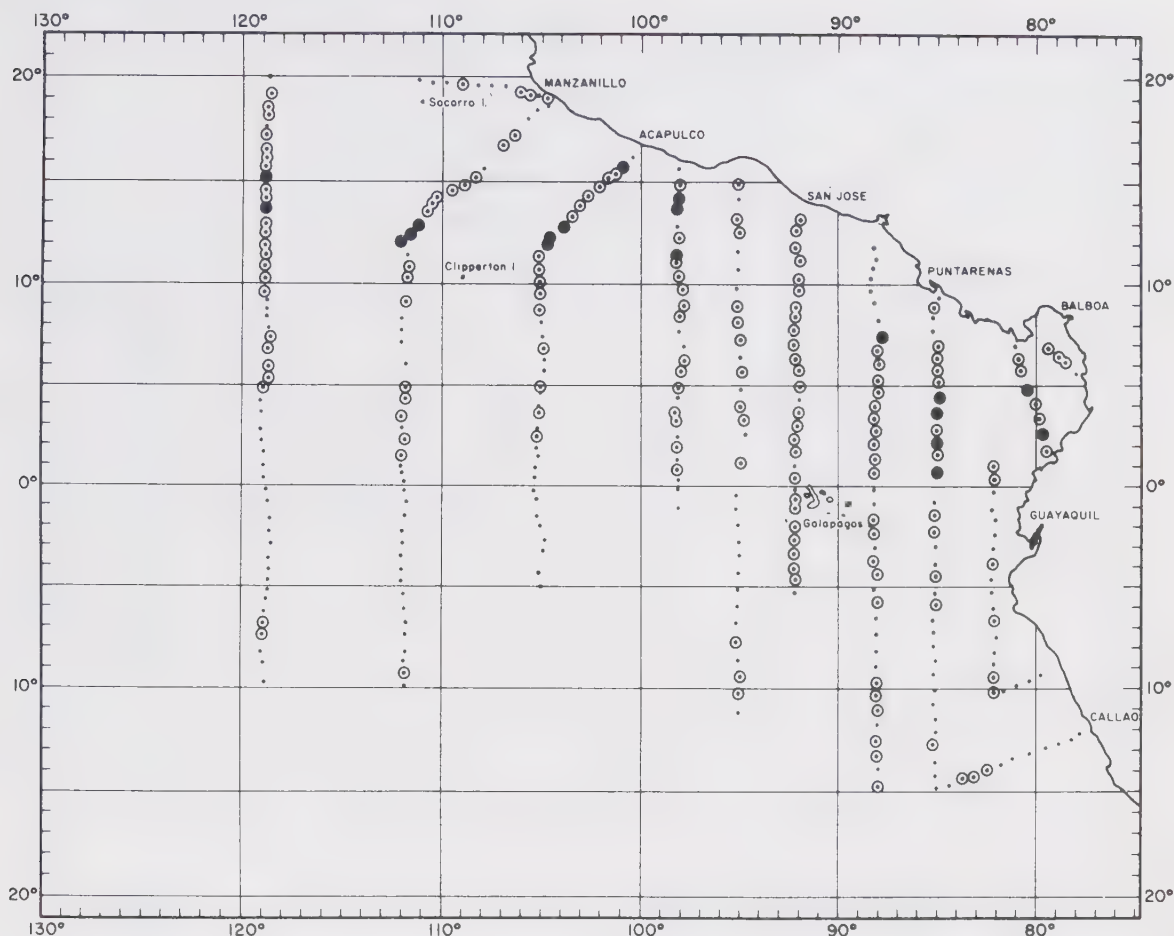


FIGURE 9.—Distribution of larvae of the stomiatoid genus *Idiakanthus* sp. on ETP II. Collections of 1-10 larvae are shown as open circles with dot in center, collections of 11 or more larvae as large solid circles; negative hauls are shown as small solid circles.

constituents: *Astronesthidae*, *Bathophilus filifer* (Garman), and *Stomias* sp.

Stomias larvae (43 occurrences, 177 larvae) were most abundant in the inner pattern. Larvae of three categories of *Melanostomiidae* were identified to the genus or species level. The most common of these were larvae of *Bathophilus filifer* (Garman) (104 occurrences, 310 larvae). Larvae of *Eustomias* spp. (10 occurrences, 19 larvae) represented several species, whereas larvae of *Leptostomias* sp. (8 occurrences, 17 larvae) were those of a single species.

Approximately half of the stomiatoid larvae (140 occurrences, 511 larvae) were not identified below the subordinal level. These were mostly small or damaged specimens; some of the unidentified stomiatoid larvae possibly are those of *Malacosteidae*.

13. EVERMANNELLIDAE (17 occurrences, 67 larvae)

The majority of evermannellid larvae were

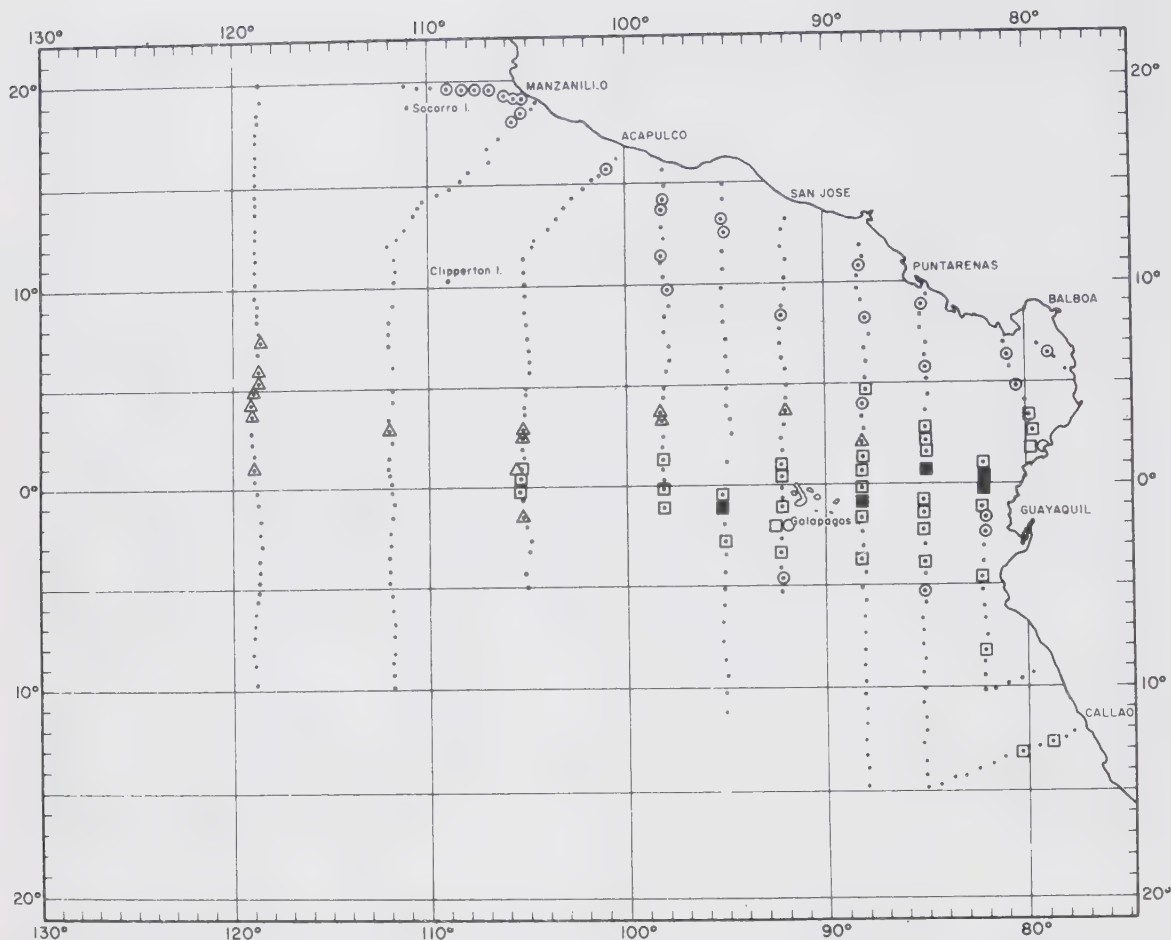


FIGURE 10.—Distribution of larvae of the myctophiform families Evermannellidae (open triangle with dot), and Scopelosauridae (open squares with dot, 1-25 larvae, closed squares, 26 or more larvae) and of the perciform family, Labridae (open circle with dot); negative hauls are shown as small solid circles.

taken on the outer line of stations along long 119°W; the remainder were taken in an equatorial band between lat 2°S and 4°N (Figure 10). This distribution is less widespread than that encountered on ETP I; however, 17 of the records of occurrence on ETP I were in the southern portion of the pattern not covered on ETP II.

14. MYCTOPHIDAE (352 occurrences, 64,009 larvae)

Larvae of Myctophidae were more abundant

on ETP II than on ETP I; the increase in abundance of myctophid larvae per haul in ETP II over ETP I was $1.63\times$. Much of the increase was due to the greater abundance of larvae of the dominant species, *Diogenichthys laternatus* (Garman), although a number of kinds of myctophid larvae were taken in somewhat greater abundance, and only a few kinds were taken in lesser numbers per haul (Table 19). To show changes in relative abundance of myctophid larvae between the two multivessel cruises, I have arranged the more common kinds in order of their relative abundance on ETP II as compared

TABLE 19.—Frequency of occurrence and relative abundance of the kinds of myctophid larvae on EASTROPAC II, and for equivalent coverage on EASTROPAC I.

Myctophid genera or species	Washington 45,000 series		Undaunted 46,000 series		Rockaway 47,000 series		EASTROPAC II total		Equivalent EASTROPAC I total	
	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae
* <i>Benthosema panamense</i>	3	72	2	88	8	971	13	1,131	7	1,027
<i>Benthosema suborbitale</i>	1	1	1	1	0	0	2	2	7	7
<i>Centrobranchus</i> sp.	1	2	0	0	0	0	1	2	0	0
* <i>Ceratoscopelus townsendi</i> complex	12	365	0	0	1	24	13	389	37	349
* <i>Diaphus</i> spp.	73	938	53	1,113	51	382	177	2,433	168	1,931
* <i>Diogenichthys atlanticus</i>	1	1	0	0	3	9	4	10	6	7
* <i>Diogenichthys laternatus</i>	92	4,661	90	16,440	138	25,865	320	46,966	302	24,315
<i>Diogenichthys</i> sp.	0	0	0	0	2	4	2	4	0	0
* <i>Gonichthys tenuiculus</i>	15	25	27	99	64	169	106	293	88	226
* <i>Hygophum atratum</i>	38	335	10	46	18	140	66	521	85	629
* <i>Hygophum proximum</i>	54	499	15	75	8	50	77	624	55	448
* <i>Lampadena</i> spp.	7	8	3	6	0	0	10	14	15	27
<i>Lampanyctus</i> spp.	84	1,013	72	1,629	135	2,692	291	5,334	271	5,262
* <i>Lepidophanes pyrosobolus</i> complex	16	53	12	73	8	12	36	138	13	41
* <i>Lobianchia</i> sp.	5	8	2	2	3	5	10	15	10	26
* <i>Lowena laurae</i>	10	15	10	14	5	8	25	37	31	41
* <i>Myctophum aurolaternatum</i>	37	85	41	144	70	445	148	674	145	529
* <i>Myctophum asperum</i>	16	118	10	62	0	0	26	180	(¹)	(¹)
* <i>Myctophum nitidulum</i>	25	300	43	274	66	717	134	1,291	(¹)	(¹)
* <i>Myctophum</i> other	11	27	6	13	0	0	17	40	117	1,042
* <i>Notolynchus valdiviae</i>	36	147	31	247	33	140	100	534	106	605
* <i>Notoscopelus resplendens</i>	14	28	29	198	35	156	78	382	54	231
* <i>Protomyctophum</i> sp.	5	7	12	22	8	15	25	44	33	74
* <i>Symbolophorus evermanni</i>	43	248	38	140	74	434	155	822	132	906
* <i>Triphoturus</i> spp.	23	40	27	132	94	652	144	824	111	356
Unidentified myctophid larvae	33	86	33	94	50	217	116	397	115	295
Disintegrated myctophid larvae	79	464	42	170	84	274	205	908	155	876
Total myctophid larvae	111	9,546	95	21,082	146	33,381	352	64,009	346	39,249

¹ Not separately tabulated.

to ETP I (comparable coverage, identical number of samples).

Genus or species of myctophid	No. in ETP II / No. in ETP I
<i>Hygophum atratum-reinhardtii</i>	0.83
<i>Notolynchus valdiviae</i>	0.88
<i>Symbolophorus evermanni</i>	0.91
<i>Lampanyctus</i> spp.	1.01
<i>Benthosema panamense</i>	1.10
<i>Ceratoscopelus townsendi</i> -complex	1.11
<i>Diaphus</i> spp.	1.26
<i>Myctophum aurolaternatum</i>	1.27
<i>Gonichthys tenuiculus</i>	1.30
<i>Hygophum proximum</i>	1.39
<i>Myctophum</i> spp. (other than <i>M. aurolaternatum</i>)	1.45
<i>Notoscopelus resplendens</i>	1.66
<i>Diogenichthys laternatus</i>	1.93
<i>Triphoturus</i> spp.	2.31

Benthosema panamense (Tåning)
(13 occurrences, 1,131 larvae)

Although larvae of this species ranked fifth in abundance among myctophid larvae, they were collected in a relatively narrow coastal band, no wider than 200 miles (Figure 11). A similar pattern of inshore, clumped distribution was encountered on ETP I (Moser and Ahlstrom, 1970, Figure 45).

Benthosema suborbitale (Gilbert)
(2 occurrences, 2 larvae)

Only two specimens of the larvae of *Benthosema suborbitale* were taken on ETP II. Larvae of this species only recently have been positively identified. The larval series was initially established by Dr. H. G. Moser from *Dana* material. Larvae are strikingly similar to *Electrona*

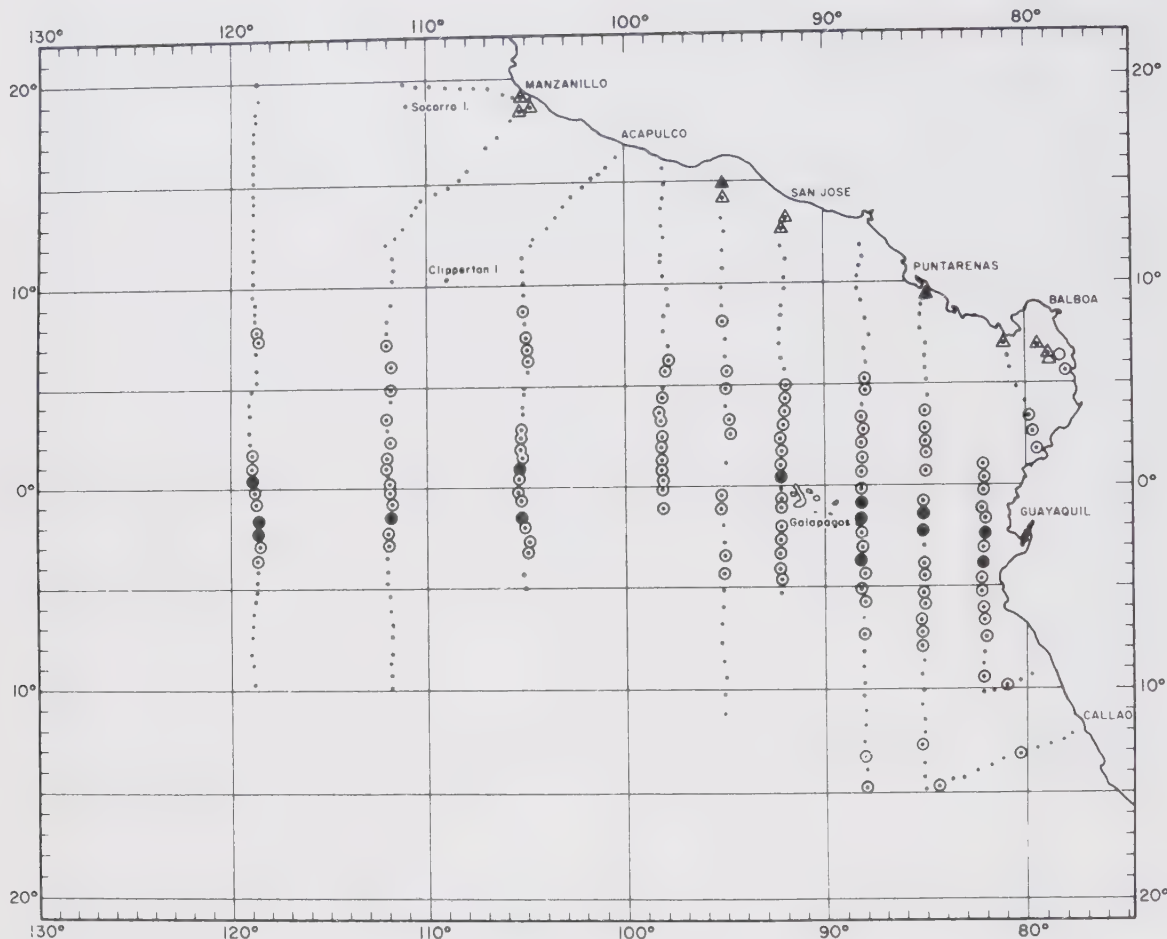


FIGURE 11.—Distribution of larvae of two species of myctophid lanternfishes. Records of occurrence of larvae of *Benthosema panamense* are shown as open triangles with dot for collections of 1-100 larvae, and as closed triangles for collections containing 101 or more larvae; records of occurrence of larvae of *Myctophum nitidulum* are shown as open circles with dot for collections of 1-25 larvae, and as large solid circles for collections containing 26 or more larvae; negative hauls are shown as small solid circles.

larvae, and earlier were confused with larvae of this genus. Most larvae included in *Electrona* sp. in the ETP I compilation were those of this species. The majority of occurrences of the larvae of this species on ETP I was in the southern, offshore portion of the ETP pattern, not covered on ETP II.

Ceratoscopelus townsendi-complex
(13 occurrences, 389 larvae)

Abbreviated coverage of the southern portion

of the EASTROPAC pattern, with coverage limited to lat 10°S or 5°S on offshore lines, cut down markedly on the occurrences of larvae of *Ceratoscopelus*, as compared with ETP I: 13 occurrences as compared with 110. All occurrences but one of *Ceratoscopelus* larvae on ETP II were obtained in the outer pattern, occupied by *Washington*: 2 at the two northernmost stations along long 119°W, and 10 in the southern portion of the pattern between lat 6° and 10°S along long 119° and 112°W (Figure 12). Both clus-

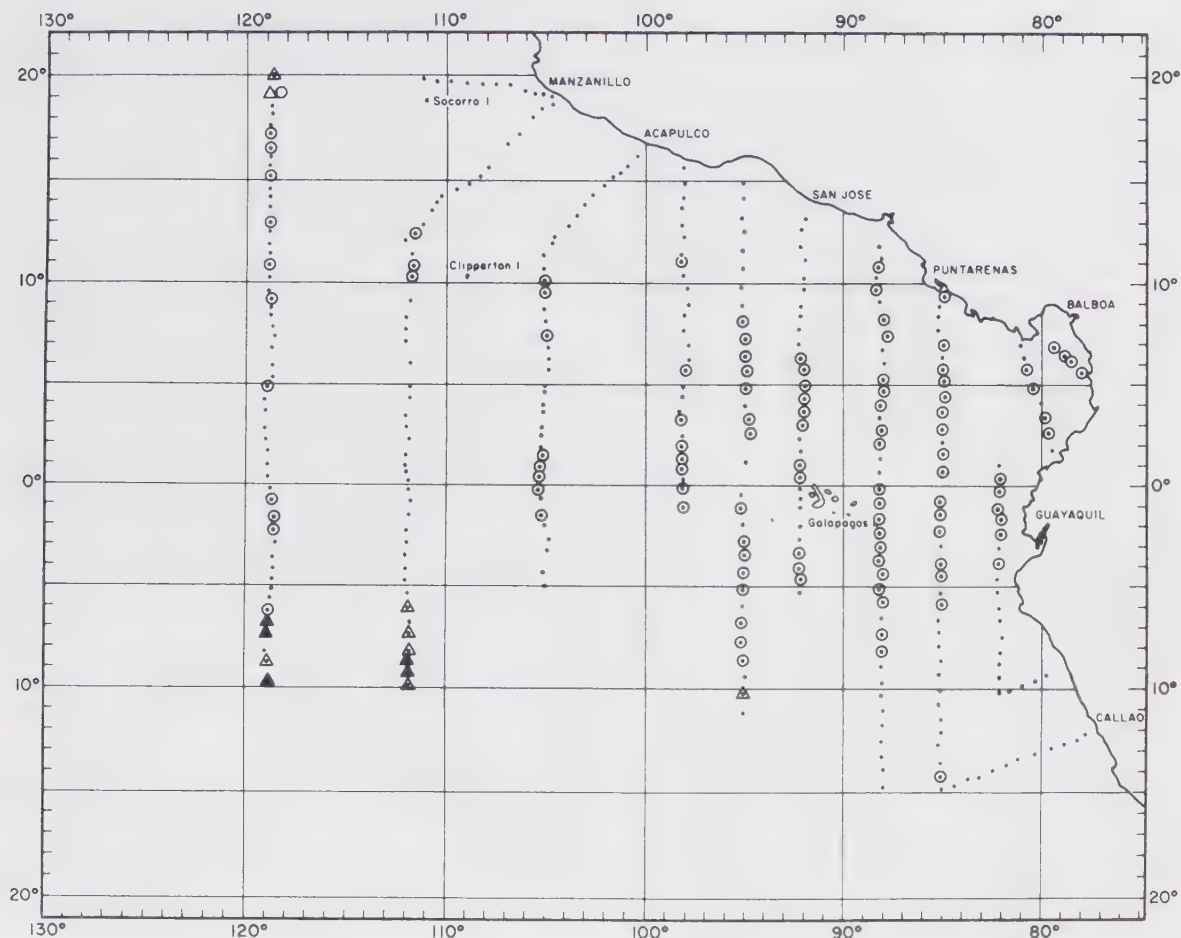


FIGURE 12.—Distribution of larvae of two species of myctophid lanternfishes. Records of occurrence of larvae of *Ceratoscopelus townsendi*-complex are shown as open triangles with dot for collections of 1-25 larvae and as closed triangles for collections of 26 or more larvae; records of occurrence of larvae of *Gonichthys tenuiculus* are shown as open circles with dot; negative hauls are shown as small solid circles.

ters of larvae occurred in the central water masses of the North and South Pacific.

Diaphus spp.

(177 occurrences, 2,433 larvae)

Larvae of *Diaphus* rank third in abundance among myctophid genera, exceeded only by *Diogenichthys* and *Lampanyctus*. Although *Diaphus* larvae were taken in half the collections

made on ETP II, occurrences and nonoccurrences tended to be clustered. Almost two-thirds of *Diaphus* larvae were obtained to the north of lat 10°N on the four outer station lines; these were predominantly larvae of *D. pacificus* Parr. The largest area of nonoccurrence was off Peru, between lat 5° and 15°S; here *Diaphus* larvae were absent from 42 consecutive stations, 47.081 to 47.197. Larvae of the subgenus *Diaphus*, which are quite distinctive, made up about 10% of the total.

Juveniles and adult *Diaphus*, separated from micronekton hauls made on ETP I, have been identified, with the cooperation of Robert Wisner of Scripps Institution of Oceanography: 15 species were represented in the collection made by *Argo*, *David Starr Jordan*, and *Alaminos* on ETP I. *D. pacificus* was, by far, the most abundant species, occurring in more collections and in larger numbers than other species of *Diaphus*. This species occurs in a broad coastal belt, 600 to 800 miles wide, from lat 20°N to the vicinity of the equator. Six species were taken offshore, between lat 5° and 20°S, in the South Pacific central water mass, including *D. rolfbolini* Wisner, *D. brachycephalus* Tåning, *D. fragilis* Tåning, *D. jenseni* Tåning, *D. schmidt* Tåning, and *D. splendidus* (Brauer). Five species were taken in an offshore equatorial belt, between lat 10°N and 5°S, including *D. garmani* Gilbert, *D. malayanus* Weber, *D. termophilus* Tåning, *D. lucidus* Goode and Bean, and *D. lutkeni* Brauer, the latter showing some admixture with central water mass species. Species belonging to subgenus *Diaphus*, tentatively identified by Wisner as *D. longleyi* Fowler and *D. mollis-nanus* complex had quite widespread distributions.

Now that the species composition of adult *Diaphus* has been clarified, life history series can be determined for the more common kinds.

Diogenichthys laternatus (Garman)
(320 occurrences, 46,966 larvae)

Larvae of *D. laternatus* were outstandingly abundant, making up 38.1% of the total fish larvae obtained on ETP II. Almost twice as many *D. laternatus* larvae were taken in equivalent coverage of the EASTROPAC region on ETP II as on ETP I; 46,966 versus 24,315 larvae. The number of collections that contained *D. laternatus* larvae, however, was not much different: 302 of 355 in ETP I as compared with 320 of 355 in ETP II. Almost one collection in three from ETP II contained over 100 *D. laternatus* larvae, and 19 collections contained over 500 larvae. Of these larger collections, 13 of 19 were taken between lat 5° and 10°N. As on

ETP I, larvae of *D. laternatus* were not taken in collections made within the central water mass of the South Pacific (Figure 13).

Diogenichthys atlanticus (Tåning)
(4 occurrences, 10 larvae)

Larvae of this species were taken more frequently on ETP I (29 occurrences, 92 larvae); however, all but six of these occurrences were in the portion of the ETP I pattern that was not covered on ETP II. The four records on ETP II were taken between lat 9° and 15°S, with two occurrences in the transitional waters of the Humboldt Current and only one occurrence offshore in the central water mass. Larvae of this species were commonly taken on MARCHILE VI off Chile (12 occurrences, 100 + larvae).

Gonichthys tenuiculus (Garman)
(106 occurrences, 293 larvae)

Larvae of *Gonichthys* had rather similar distributions and frequency of occurrences in the two multivessel EASTROPAC surveys. The majority of larvae were obtained in the inner pattern occupied by *Rockaway*, with highest frequency of occurrences in an equatorial belt between lat 5°N and 5°S (Figure 12).

Hygophum atratum (Garman)
(66 occurrences, 521 larvae)

The less extensive coverage on ETP II eliminated the area in which *H. reinhardti* (Lütken) larvae were taken on ETP I, and only larvae of *H. atratum* were observed in ETP II collections. Larvae of *H. atratum* were spottily distributed, occurring mostly in three clusters of stations: 1) between lat 15° and 20°N in the *Washington* pattern, 2) between lat 10° to 15°S in the *Rockaway* pattern, and 3) an equatorial band between lat 5°N and 5°S along long 119°, 112°, and 105°W.

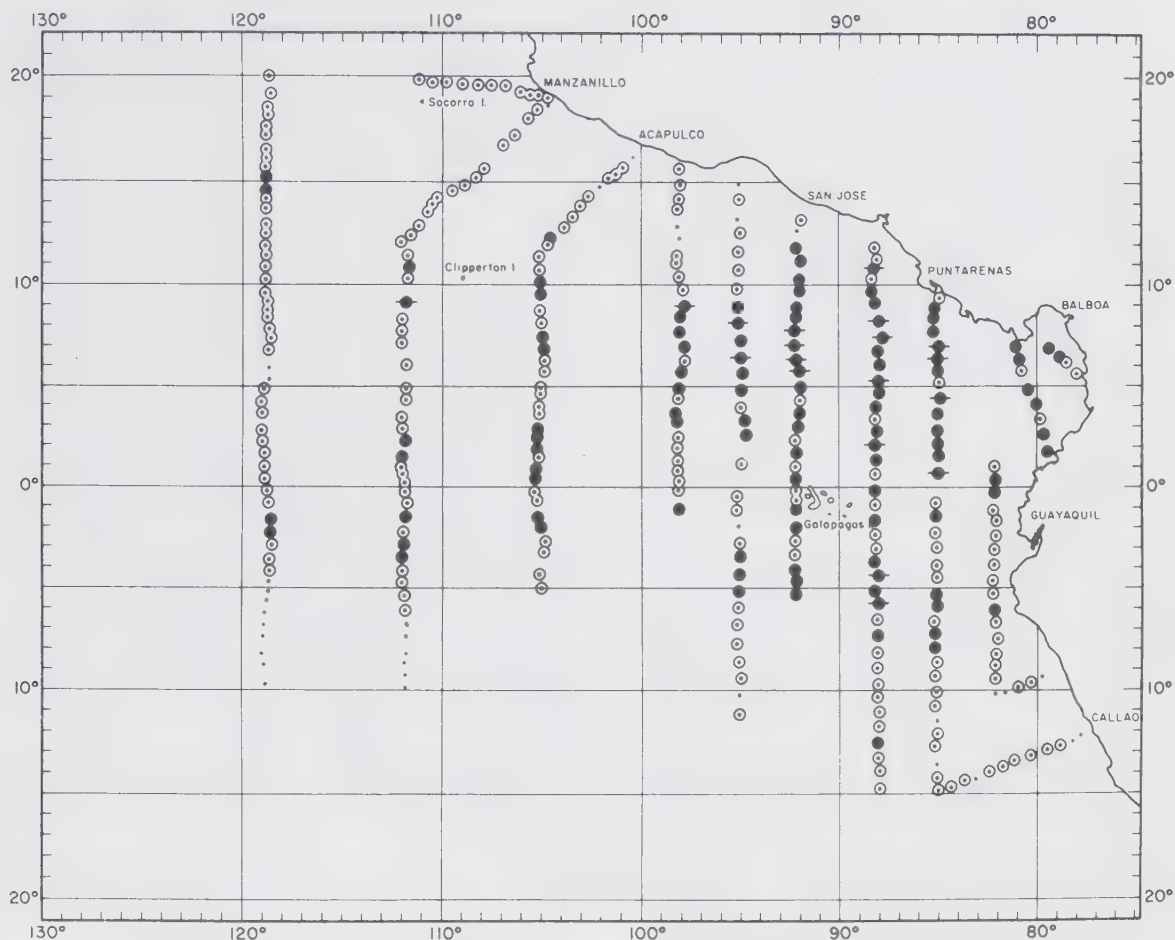


FIGURE 13.—Distribution of larvae of the myctophid *Diogenichthys laternatus* on ETP II. Three orders of abundance are shown. Open circles with dot represent counts of 1-100 larvae, large solid circles represent counts of 101-500 larvae, and large solid circles with bisecting line represent counts of 501 or more larvae; negative hauls are shown as small solid circles.

Hygophum proximum (Becker)
(77 occurrences, 624 larvae)

The distribution of larvae of *H. proximum* again is illustrated (Figure 8) to show the marked similarity in distribution to ETP I (Ahlstrom, 1971, Figure 10). Larvae of this species were decidedly more abundant in the offshore pattern occupied by *Washington* (55 occurrences, 499 larvae). As noted earlier, larvae of *H. proximum* were taken in somewhat greater

abundance in ETP II as compared to equivalent ETP I ($1.39\times$). Fully half of the occurrences and specimens of *H. proximum* larvae on ETP I was in the unreplicated portion of ETP I coverage, i.e., on the offshore line of stations along 126°W and in the offshore southern portion of the pattern. There were three occurrences of larvae on ETP II in the southern part of the *Rockaway* pattern in transitional waters of the Humboldt Current; larvae were not obtained from this area on ETP I.

Lampadena sp.
(10 occurrences, 14 larvae)

Larvae of *Lamapadena* sp. were taken on the three offshore lines in two groups—one occurring between lat 3° and 8°N and the other in the central water mass of the South Pacific between lat 7° and 10°S. A similar distributional pattern was obtained on ETP I; however, the more extensive coverage of the South Pacific central water mass on the earlier survey provided better distributional information for the southern component.

Lampanyctus spp.
(291 occurrences, 5,334 larvae)

Lampanyctus larvae rank second in abundance and in frequency of occurrence among the myctophid genera represented in the eastern tropical Pacific. *Lampanyctus* larvae were most abundant between lat 5°N and 5°S and least common between lat 10° and 20°N. The six collections of *Lampanyctus* larvae that contained over 100 specimens per collection were taken between the equator and lat 5°N. Three kinds of *Lampanyctus* larvae dominated over most of the EASTROPAC pattern. Although identification to the species level are tentative as yet, these three kinds of larvae are almost certainly those of *L. idostigma* Parr, *L. omostigma* Gilbert, and *L. parvicauda* (Parr)—three widespread tropical species of *Lampanyctus*. A quite different assemblage of *Lampanyctus* larvae was taken in the moderate number of stations occupied in the South Pacific central water mass.

Lepidophanes pyrsobolus complex
(36 occurrences, 138 larvae)

An examination of the juvenile and adult specimens of *Lepidophanes* collected on ETP I has shown that two closely related species are present—one with a very restricted distribution and the other with a widespread distribution. Nafpaktitis and Nafpaktitis (1969) found three species of *Lepidophanes* from the Indian Ocean

with common characteristics attributed to *L. pyrsobolus*. These workers considered Alcock's poorly described *L. pyrsobolus* as unidentifiable. Instead they identified their material with *L. photothorax* (Parr), *L. longipes* (Brauer), and *L. indicus* Nafpaktitis and Nafpaktitis. *L. photothorax* was taken in four ETP I collections between lat 15° and 20°S in the offshore pattern occupied by *Argo*. The specimens from the eastern Pacific agree closely with the description and illustration of this species in Nafpaktitis and Nafpaktitis (1969). These workers gave 7 + 4 as the usual combination of AO photophores on specimens from Indian Ocean material. In the EASTROPAC area all specimens examined had 6 + 4 AO photophores.

The widely distributed species in the EASTROPAC area is either *L. longipes* (Brauer) or a species closely related to *L. longipes*. The eastern Pacific form has similar luminous patches to those described for *L. longipes* from the Indian Ocean except for the luminous tissue on the head of males and the size of the infracaudal gland on some larger specimens. Luminous patches developed on the head were restricted to a single wide pair of luminous patches. On some larger specimens the infracaudal gland began under the last AO photophore and was conspicuously larger than those observed by Nafpaktitis and Nafpaktitis (1969) on Indian Ocean material. AO photophores were usually 5 + 4; gill raker counts were 5 + 1 + 11 to 13.

Two kinds of *Lepidophanes* have been observed in the EASTROPAC area, although only one kind was taken commonly. Larvae of the latter have been assigned to *L. longipes* (?).

Lobianchia spp.
(10 occurrences, 15 larvae)

Larvae of *Lobianchia*, although uncommon in the eastern tropical Pacific, have a fairly widespread distribution in two separated areas: 1) in an equatorial belt between lat 3°S and 6°N (8 occurrences) and 2) in the transitional waters of the Humboldt Current. In the latter area, two occurrences were recorded at about lat 12°

to 13°S along long 88°W, and three additional records were obtained at MARCHILE VI stations (not included in above totals). At least two species, *L. gemellari* (Cocco) and *L. dumerili* (Bleeker), and perhaps a third, are involved.

Loweina laurae (Wisner)
(25 occurrences, 37 larvae)

Wisner (1971) has separated the eastern Pacific species of *Loweina* from *L. rara* (Lütken). Although the two species are basically quite similar, Wisner points out that *L. laurae* has a somewhat longer head, 27.3 to 30.7% of SL versus about 25.7%, and a somewhat larger eye, averaging about 8% of SL versus about 6%. Wisner gave the distribution of *L. laurae* in the eastern Pacific as between lat 30°N and 30°S and westerly to long 150°W.

Of the 25 occurrences of larvae of *L. laurae* on ETP II, all but one occurred in a broad equatorial band between lat 7°N and 6°S (Figure 14). The isolated record was on the southernmost line of stations oriented normal to the coast occupied by *Rockaway*. This distribution is similar to that illustrated for ETP I (Moser and Ahlstrom, 1970, Figure 51). In equivalent coverage on ETP I, 31 stations yielded 41 larvae. It should be noted that larvae of *Loweina* from EASTROPAC appear to be identical with those identified as *L. rara* from other oceans; hence larval evidence does not support the separation of the eastern Pacific form as a separate species.

Myctophum spp.
(217 occurrences, 2,185 larvae)

Larvae of the genus *Myctophum* ranked fourth in abundance and third in frequency of occurrence. Larvae of *M. aurolaternatum* Garman (148 occurrences, 674 larvae) were taken more frequently but in lesser amounts than larvae of *M. nitidulum*-complex (134 occurrences, 1,291 larvae). Larvae of *M. aurolaternatum* were taken in all parts of the EASTROPAC pattern, but in largest numbers between the equator

and lat 5°N. Most larvae of *M. nitidulum*-complex were taken in a broad equatorial band between lat 8°N and 5°S (Figure 11). The distribution, however, had a southerly extension to the bottom of the pattern in the area of the Humboldt Current. Larvae of *M. asperum* Richardson (26 occurrences, 180 larvae) were taken in an offshore equatorial tongue, extending seaward from long 98°W to its widest extent (lat 2°S to 7°N) along long 119°W (Figure 3). The remainder of *Myctophum* larvae (17 occurrences, 40 larvae) belong to two and possibly three species. One group of these occurred in the offshore equatorial tongue, along with larvae of *M. asperum*; the other group occurred between lat 7° and 10°S in the offshore *Washington* pattern. The latter group includes larvae of both *M. lychnobium* Bolin and *M. brachygnathos* (Bleeker).

Only larvae of *M. aurolaternatum* were separately tabulated for equivalent ETP I coverage (145 occurrences, 529 larvae). Both the distribution of *M. aurolaternatum* larvae and their frequency of occurrence were similar for the two multivessel surveys, although abundance was moderately greater on ETP II, 1.9 versus 1.5 larvae per haul. This pattern of greater abundance on ETP II also held for the remainder of the larvae of *Myctophum*, 4.3 versus 2.9 larvae per haul.

Notolychnus valdiviae (Brauer)
(100 occurrences, 534 larvae)

Larvae of the wide-ranging oceanic species are seldom taken closer to shore than 200 miles. On ETP II, the majority of records were from an equatorial tongue that extended between lat 10°S and 10°N in the offshore *Washington* pattern, but shoreward of this (long 105° to 85°W) the distribution narrowed to between lat 2°S and 8°N, with the majority of occurrences between lat 2° and 6°N. A second group of larvae were sampled in the southern portion of the *Rockaway* pattern between lat 9° and 15°S. Only two occurrences of *Notolychnus* larvae were noted in 85 stations occupied by all vessels between lat 20° and 10°N. Distribution of *Notolychnus*

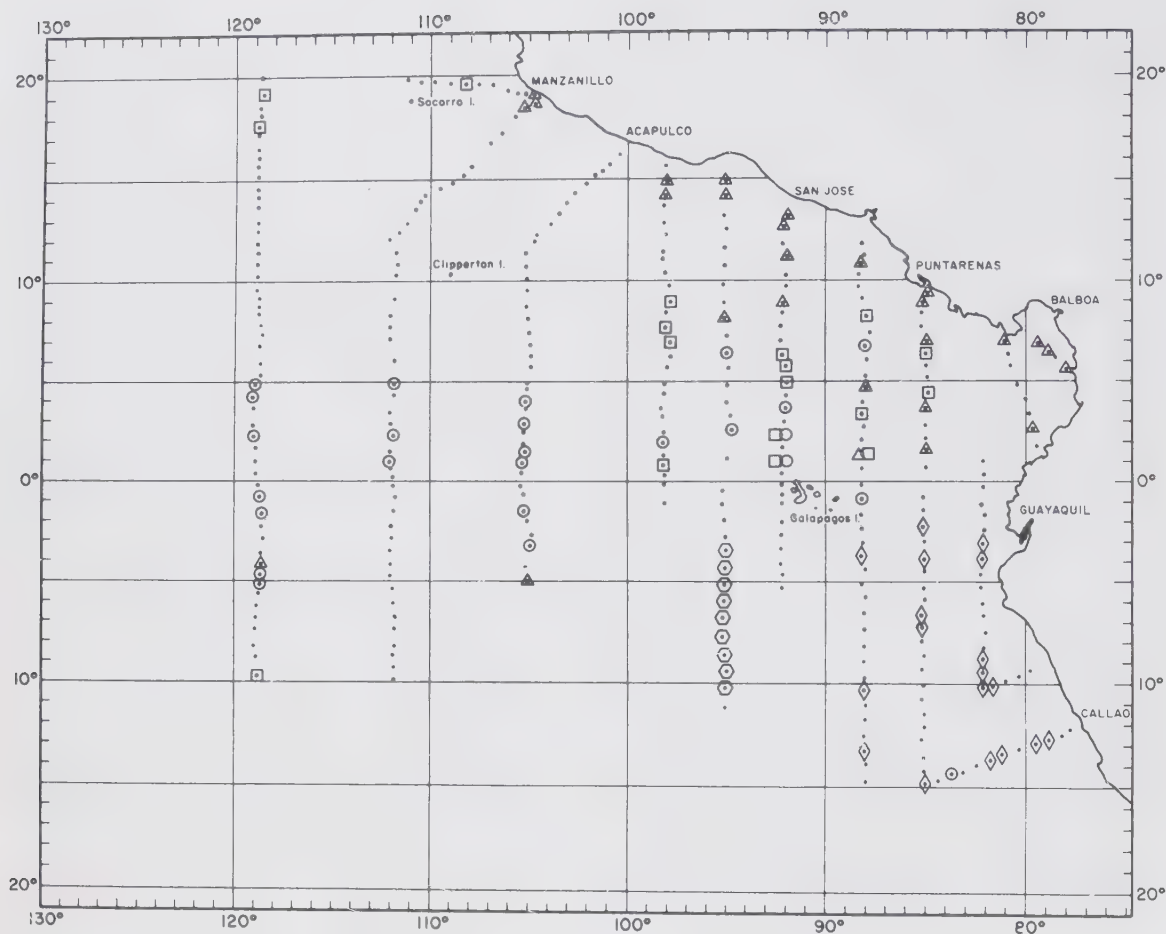


FIGURE 14.—Distribution of larvae of the myctophid, *Loweina laurae* (open circle with dot), of the scomberesocids, *Scomberesox saurus* (open diamond with dot), and *Cololabis adocetus* (open hexagon with dot) and of the anguilliform families Congridae (open triangle with dot) and Nemichthyidae (open square with dot); negative hauls are shown as small solid circles.

larvae was illustrated for ETP I coverage (Ahlstrom, 1971, Figure 11). In the portion of ETP I pattern also covered on ETP II, frequency of occurrence and distribution of *Notolychnus* larvae were quite similar: 1.7 versus 1.5 larvae.

Notoscopelus resplendens (Richardson)
(78 occurrences, 382 larvae)

As on ETP I, most larvae of *N. resplendens* were taken in an equatorial belt, between lat 5°N

and 5°S (65 occurrences, 364 larvae). A second center of occurrence was at the southern portion of the *Rockaway* pattern between lat 9° and 15°S. Except that the distribution of the main group of *Notoscopelus* larvae is more definitely centered on the equator, the distribution of larvae of *Notoscopelus* and *Notolychnus* are quite similar. No larvae of *Notoscopelus* were taken north of lat 6°N. Moderately more larvae of *Notoscopelus* were taken on ETP II, 1.1 versus 0.7 larvae per haul.

Protomyctophum sp.

(25 occurrences, 44 larvae)

For most kinds of myctophids, the distributional patterns of larvae are so similar in the two multivessel EASTROPAC survey cruises that distributional information from ETP II merely reinforced that obtained on ETP I. Distribution of *Protomyctophum* larvae affords another example of this. All but two of the occurrences lie between lat 10°N and 5°S, the zone in which all *Protomyctophum* larvae were obtained on ETP I. As noted in Ahlstrom (1971), the larvae were all of a kind, belonging to a perhaps undescribed species of *Protomyctophum*, subgenus *Hierops*. Wisner (1971) described two new species of *Protomyctophum*, subgenus *Hierops* from the eastern Pacific: *P. chilensis* from off Chile about lat 33°S and *P. beckeri* from the vicinity of the Hawaiian Islands. It is not known as yet whether the form from EASTROPAC is referable to either of these.

Symbolophorus evermanni (Gilbert)

(155 occurrences, 822 larvae)

Larvae of *Symbolophorus* were absent from a wide coastal strip off Mexico and a narrower coastal strip off Peru, but were taken at most stations in the remainder of the ETP II pattern. The distribution was rather similar to that illustrated for ETP I (Ahlstrom, 1971, Figure 12); the frequency of occurrence was slightly lower on equivalent ETP I (37% positive hauls versus 44%), but the average abundance per haul was slightly higher (2.6 versus 2.3 larvae). However, in the ETP I stations without counterparts in ETP II, frequency of occurrence was higher than in the remainder of the ETP I pattern (63% versus 37%) and average abundance per haul was higher (4.5 versus 2.6 larvae).

Triphoturus spp.

(144 occurrences, 824 larvae)

Larvae of *Triphoturus oculus* (Garman) were taken in most hauls made between lat 5°N

and 15°S off Ecuador and Peru and offshore to the vicinity of the Galapagos Islands. Larvae of this species, which appear to be more exclusively restricted to the transition waters of the Humboldt Current than are those of other myctophids sampled in the EASTROPAC pattern, also may exhibit the most marked seasonal change in relative abundance. Other *Triphoturus* larvae, sampled mostly offshore, were taken in slightly lesser abundance than on ETP I.

16. PARALEPIDIDAE

(247 occurrences, 2,535 larvae)

Larvae of Paralepididae ranked sixth in abundance and contributed over 2% of the total. Larvae were taken throughout the ETP II pattern, but most commonly in an equatorial band between lat 5°N and 5°S; all collections of larvae exceeding 25 larvae per haul were obtained from this band. Fewest larvae were taken in the southern portion of the inner pattern, below about lat 7°S. Because of limited coverage of the South Pacific central water mass on ETP II, no material was obtained of *Sudix atrox* Rofen (see Ahlstrom, 1971, Figure 7 for distribution of larvae of this species on ETP I). A detailed study of the species composition of the paralepidid material from EASTROPAC surveys has not been made.

17. SCOPELARCHIDAE

(134 occurrences, 298 larvae)

Larvae of Scopelarchidae were taken throughout the area surveyed on ETP II. As noted for ETP I (Ahlstrom, 1971, p. 32-33), larvae of five or six kinds of scopelarchids were obtained, usually in small numbers per haul. On ETP II, only 6 of 133 positive hauls contained over 5 larvae (6 to 12 larvae), and over 80% of the hauls contained 1 to 3 larvae per haul.

18. SCOPELOSAURIDAE

(40 occurrences, 390 larvae)

Larvae of Scopelosauridae were taken in more

hauls and in much larger numbers than on equivalent ETP I (6 occurrences, 13 larvae). As shown in Figure 10, most occurrences were in an equatorial band between lat 5°N and 5°S and offshore to long 105°W; the five hauls containing 25 or more larvae were obtained within 2° of the equator. Only one kind of *Scopelosaurus* larva was obtained on ETP II. Larvae of *Scopelosaurus* superficially resemble paralepidid larvae—both have elongate larvae with a short gut that increases in relative length in older larvae. However, *Scopelosaurus* larvae differ in several significant ways from paralepidid larvae. *Scopelosaurus* larvae never develop patches of pigment above the intestinal tract, whereas these patches are a striking feature of paralepidid larvae; the eyes of *Scopelosaurus* larvae are narrowed, whereas they are round in most paralepidid larvae; also the intestinal tract does not increase in relative length nearly as much in older stage *Scopelosaurus* larvae as in paralepidid larvae.

19. SYNODONTIDAE (14 occurrences, 60 larvae)

Larvae of *Synodus* spp. occurred in a coastal band along the extent of the ETP II pattern (Figure 5). Six species of *Synodus* are known to occur in the eastern Pacific. Several kinds of *Synodus* larvae were taken in the EASTROPAC collections, mostly small specimens. Until more older-stage larvae are obtained, it will not be possible to work out life history series.

21. ANGUILLIFORMES (EEL LEPTOCEPHALI) (81 occurrences, 151 larvae)

Eel leptocephali, although conspicuous members of the larval fish fauna, are not common in the EASTROPAC pattern: they contributed only 0.12% of the total ETP II larvae. Leptocephali of seven families of true eels of the order Anguilliformes, suborder Anguilloidei, were identified from the micronekton net collections of ETP II. The micronekton net collections from ETP I contributed three times as many lepto-

cephali as the regular net hauls; a total of 10 families was represented in the combined ETP I collections, including the 7 discussed below and in addition Derichthyidae, Muraenesocidae, and Nettastomidae. The record of occurrence and counts by family of eel leptocephali on all positive stations is contained in Appendix Table 5, and summarized in Table 20. The distributions of larvae of the seven families taken in ETP II collections are shown in Figures 14 and 15.

Congridae (28 occurrences, 42 larvae)

This family ranked first in frequency of occurrence among eel leptocephali and second in relative abundance. Most congrid larvae were identifiable to genus. The breakdown was as follows: *Ariosoma* sp. (5 occurrences, 8 larvae), *Bathyconger* sp. (3 occurrences, 4 larvae), *Gnathopis* sp. (1 occurrence, 1 larva), *Hildebrandia* (10 occurrences, 18 larvae), *Paraconger* (4 occurrences, 5 larvae), and genus uncertain (6 occurrences, 6 larvae). All but two occurrences were from north of the equator, and most specimens were taken in a broad coastal band. However, offshore oceanic occurrences of congrid leptocephali were more frequent on ETP I than on ETP II.

Moringuidae (3 occurrences, 3 larvae)

One occurrence of leptocephali of the moringuid genus *Neoconger* was off Manzanillo, Mexico, the other two near Panama Bay.

Muraenidae (5 occurrences, 6 larvae)

Although adults of Muraenidae are known to have a wide distribution in the eastern Pacific, the few leptocephali taken on ETP II were confined to a narrow tongue extending offshore between lat 7° and 10°N in the northeast quadrant.

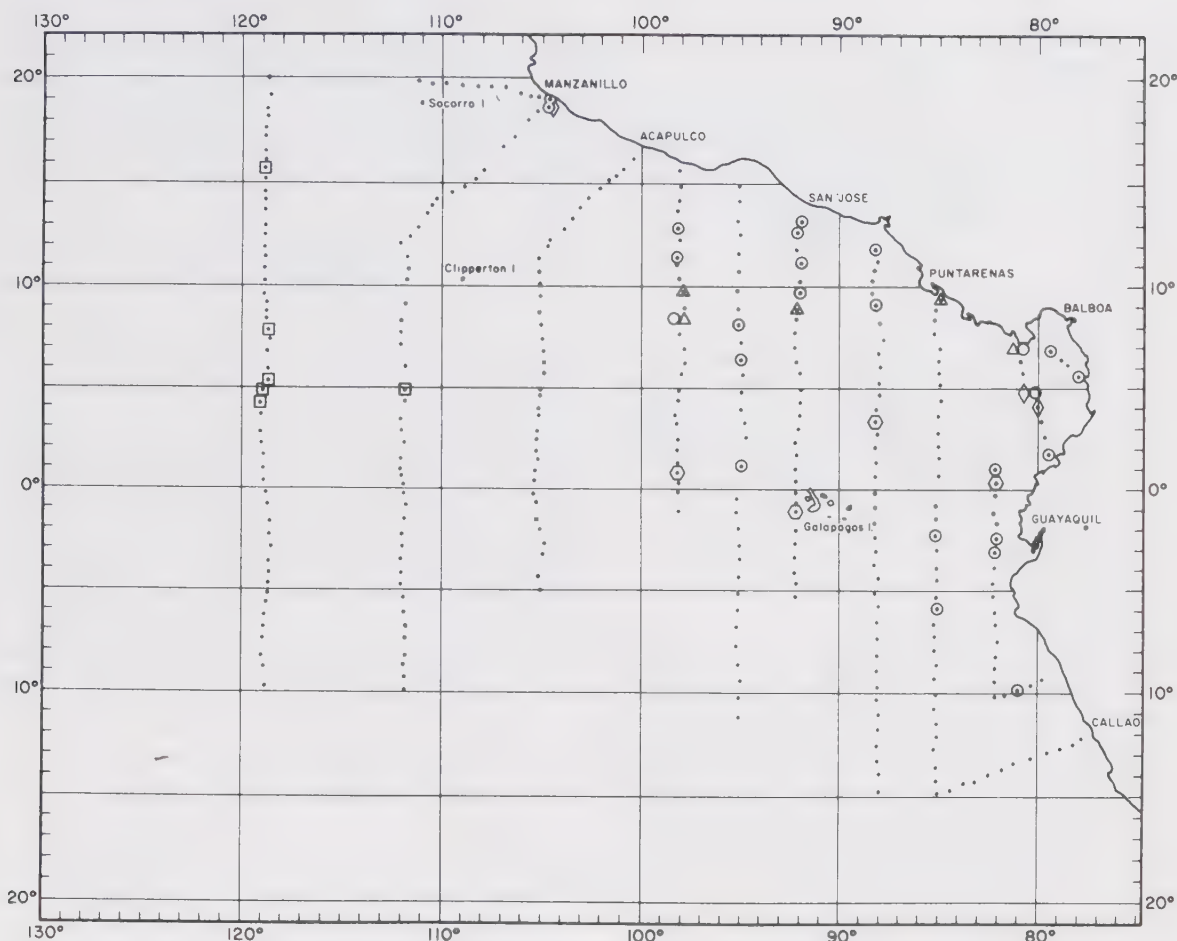


FIGURE 15.—Distribution of eel leptocephali of the anguilliform families: Moringuidae (open diamond with dot), Muraenidae (open triangle with dot), Opichthidae (open circle with dot), Serrivomeridae (open square with dot), and Xencongridae (open hexagon with dot); negative hauls are shown as small solid circles.

TABLE 20.—Familial composition of eel leptocephali taken on the second multivessel EASTROPAC survey, summarized by vessel pattern.

Family	Washington 45,000 series		Undaunted 46,000 series		Rockaway 47,000 series		Total EASTROPAC II	
	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae
Congridae	3	6	9	11	16	25	28	42
Moringuidae	1	1	0	0	2	2	3	3
Muraenidae	0	0	3	3	2	3	5	6
Nemichthyidae	4	5	9	9	6	7	19	21
Ophichthidae	2	8	7	12	17	29	26	49
Serrivomeridae	6	8	0	0	0	0	6	8
Xencongridae	0	0	2	2	2	2	4	4
Family unknown	4	5	4	5	5	8	13	18
Total	16	33	30	42	35	76	81	151

Nemichthyidae
(19 occurrences, 21 larvae)

Although eels of this family are widely distributed in offshore oceanic waters, most occurrences of leptocephali (14 of 19) were in the northeast quadrant, between lat 0° and 10°N.

Ophichthidae
(26 occurrences, 49 larvae)

Ophichthid leptocephali were taken in a broad coastal band between Manzanillo, Mexico, and Central Peru (lat 10°S). They ranked first in relative abundance among eel leptocephali and second in frequency of occurrence.

Serrivomeridae
(6 occurrences, 8 larvae)

Most occurrences of serrivomerid leptocephali (5 of 6) were on the outer line of the ETP II pattern, along long 119°W, and the remaining occurrence was along long 112°W. In contrast to nemichthyid leptocephali which may grow to 300 or 400 mm long, leptocephali of Serrivomeridae rarely exceed about 60 mm.

Xenocoagridae
(4 occurrences, 4 larvae)

The few occurrences of leptocephali of *Chlopsis*, the sole representative of this family, were within 4° of the equator.

22. MELAMPHAIDAE
(284 occurrences, 1,365 larvae)

Larvae of Melamphaidae ranked fourth in frequency of occurrence, eighth in relative abundance. Larvae were distributed throughout the ETP II pattern (Figure 16), and occurred in 80% of the collections. Most collections contained only moderate numbers of larvae—the average number of larvae per positive

haul was only 4 to 8. The majority of hauls containing larger numbers of larvae (11 or more per haul) were taken within 5° of the equator (Figure 16). Melamphaid larvae were represented by four genera: *Melamphaes*, *Scopelogadus*, *Scopeloberyx*, and *Poromitra*.

23. TRACHICHTHYIDAE
(11 occurrences, 70 larvae)

The big-headed larvae of a representative of this family were taken at 11 stations on the two inner lines of the *Rockaway* pattern, between about lat 2° to 8°S (Appendix Table 3). They appear to be larvae of *Trachichthys mento* Garman, initially described from the Gulf of Panama. Bussing (1965) supplemented Garman's description, utilizing 53 specimens (55 to 104 mm) collected at *Eltanin* Station 34 at lat 07°45' to 07°48'S, long 81°23'W. Parin (1971) also obtained material of this species in the eastern tropical Pacific from off South America.

25. BREGMACEROTIDAE
(160 occurrences, 3,062 larvae)

Larvae of Bregmacerotidae ranked fifth in abundance and contributed 2.5% of fish larvae on ETP II. The majority of larvae was taken to the north of the equator, with three inshore collections contributing over 70% of the total. These collections of 927, 753, and 511 larvae were exclusively *Bregmaceros bathymaster* Jordan. Larvae of this species were distributed in a broad coastal band in the northern half of the EAS-TROPAC pattern. As noted in the ETP I report, larvae of five species of *Bregmaceros* are distributed in the eastern tropical Pacific.

27. SCOMBERESOCIDAE
(27 occurrences, 153 specimens)

Two species of Scomberesocidae were taken on ETP II—*Scomberesox saurus* L. (18 occurrences, 52 specimens) and *Cololabis adocetus* Böhlke (9 occurrences, 101 specimens). The

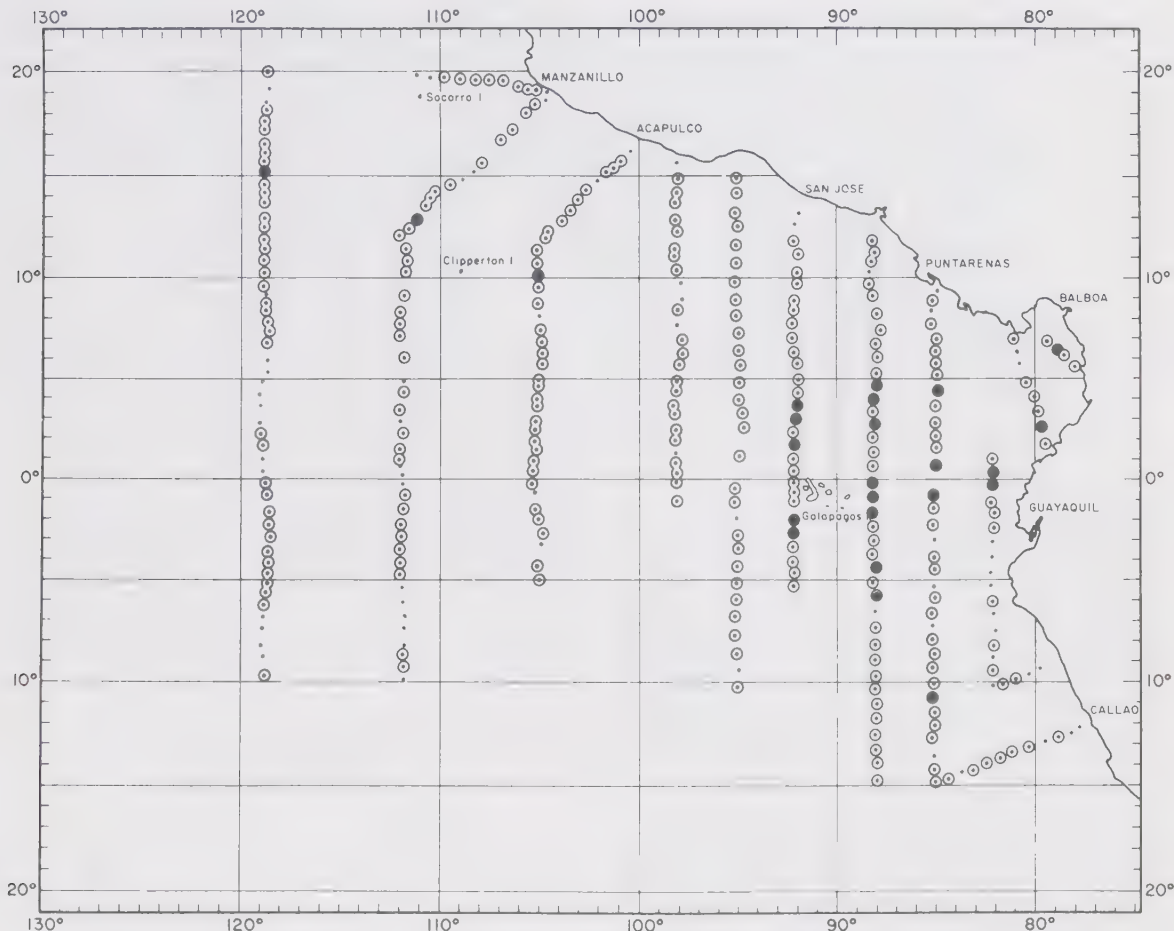


FIGURE 16.—Distribution of larvae of the beryciform family Melamphaidae on ETP II. Collections of 1-10 larvae are shown as open circles with dot, collections of 11 or more larvae as large solid circles; negative hauls are shown as small solid circles.

word "specimen" is used intentionally because some juveniles as well as larvae are included in the above counts. A number of the specimens were x-rayed in order to obtain vertebral counts to verify identification. All occurrences of the small tropical saury, *Cololabis adocetus*, were along long 95°W at nine contiguous stations (Figure 14); surface temperatures ranged between 19.5° and 21.5°C at these stations. *Scomberesox* larvae occurred in a broad coastal belt, shoreward of *C. adocetus*, extending from near the equator to the southernmost line occupied on ETP II (Figure 14); surface temperatures

ranged between 15.8° and 19.5°C at these stations. Actually *Scomberesox* eggs and larvae were commonly taken in the pattern occupied by *Yelcho* off Chile as part of ETP II—MARCHILE VI. Collections obtained from surface tows as well as from oblique net hauls were available from MARCHILE VI. Five short lines of stations normal to the trend of the Chilean coastline were occupied on MARCHILE VI, between lat 18°30' and 33°S. *Scomberesox* eggs and larvae were sampled best in surface hauls. *Scomberesox* eggs were taken in 17 of 20 surface hauls and *Scomberesox* larvae in 10 surface

TABLE 21.—Measurements of eggs of *Scomberesox saurus* collected on EASTROPAC II, including collections made off Chile by *Yelcho* (MARCHILE VI).

Collection	Type of haul	Locality of collection		Number eggs measured	Range in egg diameter (mm)	Average diameter (mm)	Surface water temperature (°C)
		Lat S	Long W				
MAR. 5.4	Surface	33°05.3'	73°20.5'	25	2.41-2.67	2.52	12.50
MAR. 4.4	Oblique	28°30.6'	72°43.2'	23	2.39-2.65	2.52	12.09
ETP 47.177	Oblique	06°35.0'	85°08.5'	31	2.31-2.60	2.44	18.14
MAR. 4.1	Surface	28°30.2'	71°40.1'	30	2.26-2.62	2.43	11.93
MAR. 3.2	Surface	23°42.5'	71°35.0'	25	2.24-2.45	2.36	14.39
ETP 47.145	Oblique	14°17.8'	83°03.7'	14	2.26-2.43	2.35	18.28
MAR. 1.8	Surface	18°27.6'	73°06.1'	25	2.24-2.51	2.34	15.81 (10 m)
ETP 47.134	Oblique	12°56.5'	79°27.8'	16	2.21-2.48	2.34	16.62
ETP 47.103	Oblique	10°09.0'	82°08.5'	25	2.26-2.45	2.34	18.32
ETP 47.107	Oblique	09°50.0'	80°53.0'	16	2.26-2.46	2.34	17.74
MAR. 2.1	Surface	20°09.0'	70°31.8'	25	2.15-2.45	2.33	15.77 (10 m)
MAR. 1.4	Surface	18°32.0'	71°42.0'	25	2.17-2.45	2.32	15.92 (10 m)
MAR. 2.4	Surface	20°10.8'	71°33.2'	25	2.19-2.45	2.32	15.74 (10 m)

hauls on MARCHILE VI. Hence young of *Scomberesox* have a north-south extent off South America of at least 1,860 miles.

Scomberesox eggs are approximately round and occur singly—lacking the attachment filaments characteristic of most eggs of fishes in the suborder Exocoetoidei (see in this regard Orton, 1964). The egg shell, however, is ornamented with minute closely spaced swellings. Eggs from 13 collections were measured (eggs measured in widest dimensions as they were not truly spherical); the data are summarized in Table 21. The range in egg size was from 2.15 to 2.67 mm; the range in egg diameter means for the 13 collections was from 2.32 to 2.52 mm. Eggs in the majority of collections (9 of 13) were quite similar in average diameters, ranging between 2.32 and 2.36 mm. Three of the four collections of eggs with larger average diameters were taken on the southernmost two lines of the *Yelcho* pattern. However, the collection of eggs made nearest to the equator (lat 6°35') also was in this group of larger eggs.

30. APOGONIDAE

(66 occurrences, 283 larvae)

This family contains both oceanic and coastal species. Larvae of coastal apogonids were taken in four hauls off Central America and northern South America. The remainder of the larvae (62 occurrences, 278 larvae) were those of

Howella pammelas (Heller and Snodgrass). Larvae of this species were most common to the north of the equator in a broad band extending offshore between 0° and lat 9°N. Only three occurrences were found to the north of this band and 11 to the south. This species was not limited in its distribution to particular water masses.

34. CARANGIDAE

(36 occurrences, 224 larvae)

Larvae of the pilotfish, *Naucrates ductor* (L.), with 18 occurrences, 27 larvae (Figure 17), was the most widely distributed carangid on ETP II. Over half of the carangid larvae were obtained at two coastal stations—45 larvae at 46.135 and 69 larvae at 47.527. As on ETP I, a number of kinds of carangid larvae were taken, including *Chloroscombrus orqueta* Jordan and Gilbert, *Selene brevoorti* (Gill), and *Caranx* spp.

37. CORYPHAENIDAE

(109 occurrences, 185 larvae)

Larvae of the dolphin, *Coryphaena* spp., were taken almost exclusively to the north of the equator (105 occurrences, 180 larvae) on ETP II; three of the four occurrences to the south of the equator were at stations immediately adjacent to the equator. *Coryphaena* larvae were

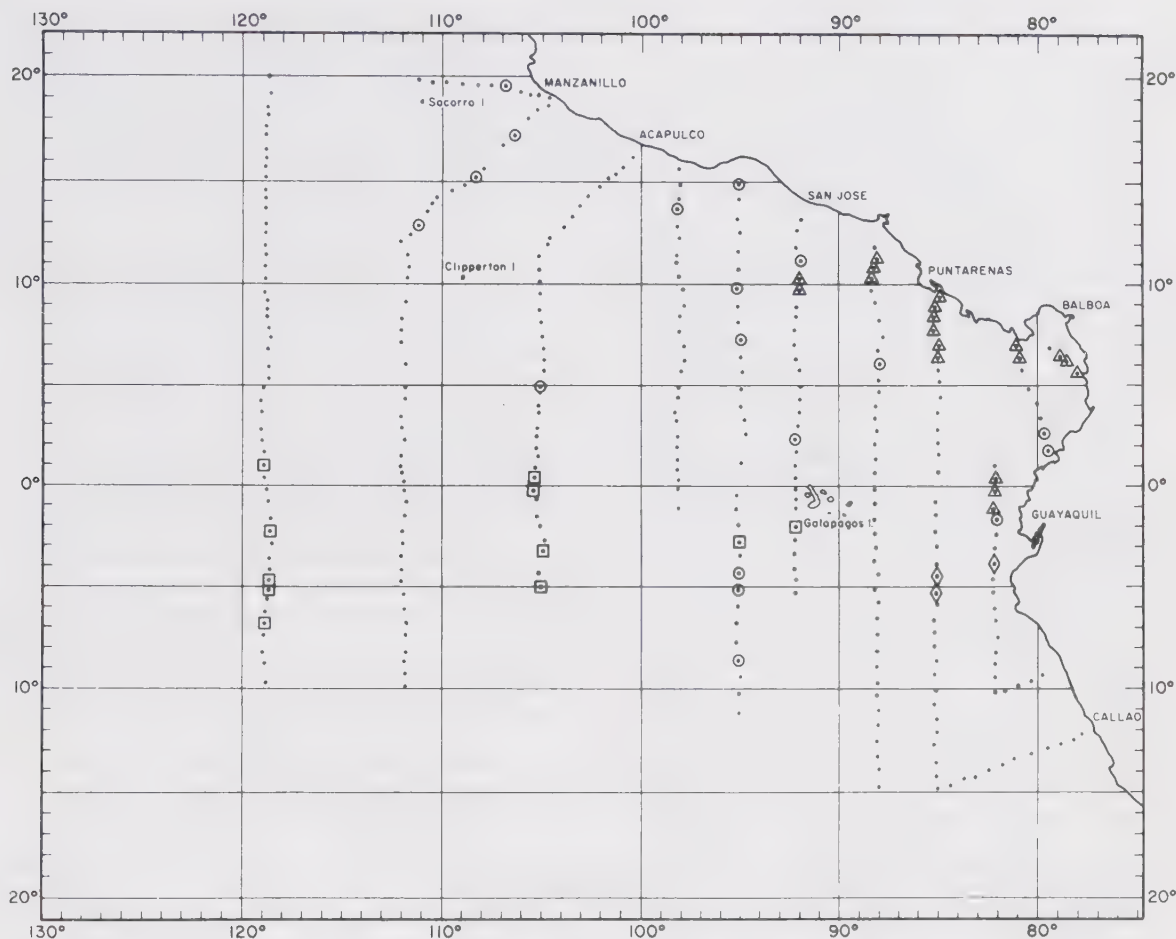


FIGURE 17.—Distribution of larvae of the carangid, *Naucrates ductor* (open circle with dot), of the tetragonurid, *Tetragonurus* spp. (open square with dot), and of the trichiurids, *Lepidopus* sp. (open diamond with dot) and *Trichiurus lepturus* (open triangle with dot); negative hauls are shown as small solid circles.

taken throughout the coverage on ETP I but at a lesser proportion of the stations; in equivalent coverage, 97 larvae were taken in 67 collections on ETP I. Dolphin larvae provide one of the more striking examples of a marked difference in the distributional pattern of larvae as between ETP I and ETP II.

Eggs and newly hatched larvae have been described for *Coryphaena hippurus* L. by Mito (1960). The eggs are 1.2 to 1.6 mm, with a single oil globule 0.3 to 0.4 mm. The larvae are heavily pigmented, even at hatching. We have not found distinguishing characters to separate

the larvae of *C. hippurus* from those of *C. equiselis*, hence have labelled our material as *Coryphaena* spp. After the vertebral column is developed, definitive identification can be made: *C. hippurus* has 31 vertebrae, *C. equiselis* has 33 (Collette, Gibbs, and Clipper, 1969). Parin (1968) reports that *C. hippurus* reproduces only in the littoral zone and that *C. equiselis* is the offshore spawner. If this pattern of spawning holds for the eastern Pacific, then the majority of larvae taken on EASTROPAC cruises were those of *C. equiselis*. As noted for this family in the first EASTROPAC paper (ETP I, 38) the

majority of the specimens obtained were early stage larvae, hence spawned in the area of collection.

38. GEMPYLIDAE

(112 occurrences, 370 larvae)

Two kinds of gempylid larvae were widely distributed in the EASTROPAC area on ETP II: larvae of *Gempylus serpens* Cuvier and Valenciennes (71 occurrences, 152 larvae) and *Nealotus tripes* Johnson (66 occurrences, 218 larvae).

Larvae of both species had a higher frequency of occurrence and greater abundance on ETP II. Distribution within the EASTROPAC area also was different in the two multivessel surveys. The more widespread distributional pattern for *Gempylus serpens* was observed from the wider-ranging ETP I survey. Over a third of the occurrences of *Gempylus* larvae were in the portion of the ETP I pattern not replicated on ETP II (Ahlstrom, 1971, Figure 13). Larvae were taken throughout the ETP I pattern with as many records from south of the equator as to the north. In contrast, only three collections were made to the south of the equator on ETP II (Figure 4), but many more collections of *Gempylus* larvae were obtained to the north of the equator, particularly in the inner pattern occupied by *Rockaway*.

Changes in distribution of larvae of *Nealotus tripes* in the two surveys were not as marked as for *G. serpens*. On both surveys the majority of the occurrences of *Nealotus* larvae were in the inner half of the ETP pattern; heaviest concentration of larvae on ETP II was in an equatorial band between circa lat 5°N and 3°S. Fewer *Nealotus* larvae were taken in the inner pattern off Peru, between circa lat 3° and 15°S, as compared with ETP I (ETP I, Figure 7).

39. GOBIIDAE

(53 occurrences, 384 larvae)

Larvae of several families of shore or bottom fishes have a much more widespread oceanic distribution than would be anticipated from the

distribution of adults. In the EASTROPAC area this applies particularly to larvae of Gobiidae, Scorpaenidae, Labridae, Bothidae, and Cynoglossidae. Based on pigmentation and meristics a minimum of eight kinds of goby larvae were taken.

42. NOMEIDAE

(229 occurrences, 1,460 larvae)

And other Stromatei (14 occurrences, 16 larvae)

Four families of stromateoid fishes were taken on EASTROPAC cruises: Amarsipidae, Nomeidae, Stromateidae, and Tetragonuridae. Three of these families contain oceanic species that are widely distributed in offshore waters; only fishes of the family Stromateidae are confined to coastal waters. Important papers dealing with stromateoid fishes include Grey (1955), Haedrich (1967, 1969), Haedrich and Horn (1969),² and Horn (1970).

In the EASTROPAC area, only the nomeids were common, occurring in about two-thirds of the collections made on ETP II. Larvae were obtained of two genera, *Cubiceps* and *Psenes*; larvae of the former were the more abundant, larvae of the latter were more diversified as to species represented.

Larvae of a species in the family Stromateidae, *Peprilus medius* (Peters), were taken at a single station on ETP II, 46.135 (2 larvae), but a larger collection was obtained at *Oceanographer* Station OP 168 (16 larvae).

Larvae of Tetragonuridae (11 occurrences, 12 larvae) occurred in an equatorial band between lat 2°N and 7°S, seaward of the Galapagos Islands (Figure 17). As noted in the first EASTROPAC report, larvae of two species were taken: *T. cuvieri* Risso and *T. atlanticus* Lowe.

Two specimens of *Amarsipus carlsbergi*, described by Haedrich (1969) as a monotypic representative of a new family Amarsipidae, were

² Haedrich, R. L., and M. H. Horn. 1969. A key to the stromateoid fishes. Woods Hole Oceanogr. Inst. Ref. #69-70, 46 p. (Unpublished manuscript.)

obtained on ETP II, and five specimens previously had been taken on ETP I. These had been identified as *Centrolophus*-like with the notation that they probably represented an undescribed form. Identification of the material as *Amarsipus carlsbergi* was made by Dr. Michael H. Horn. Since little is known about this species in the eastern Pacific, I am listing all catch localities.

ETP II = Station 45.346 at lat 14°38.2'N, long 109°37.1'W, Sept. 8, 1967, 1 specimen, 26.2 mm; Station 47.272 at lat 11°20.8'N, long 88°00.5'W, Aug. 31, 1967, 1 specimen, 15.0 mm.

ETP I = Station 11.066 at lat 06°49.8'N, long 118°55.5'W, Feb. 3, 1967, 1 specimen, 10.3 mm; Station 11.114 at lat 02°37.8'S, long 119°02.3'W, Feb. 7, 1967, 1 specimen, 30.0 mm; Station 11.306 at lat 12°03.5'N, long 126°00'W, Feb. 27, 1967, 1 specimen, 16.0 mm; Station 12.059 at lat 09°31.5'N, long 105°02.0'W, Feb. 22, 1967, 1 specimen, 7.2 mm; Station 12.246 at lat 06°12.0'N, long 112°00.5'W, Mar. 16, 1967, 1 specimen, 7.3 mm.

43. OPHIDIIDAE

(38 occurrences, 81 larvae)

A number of kinds of larvae of this complex family were taken on ETP II, mostly in a coastal band between Acapulco, Mexico, and central Peru, but six occurrences were in a loose cluster about the Galapagos Islands. Only one kind has been identified to genus as yet; this is a form with conspicuously large pectorals (11 occurrences, 15 larvae) whose larvae were clustered in the Gulf of Panama or immediately seaward. Dr. Daniel Cohen of the National Marine Fisheries Service has identified larger specimens (small juveniles) as *Brotula* sp. A characteristic of this genus observed on several specimens was the presence of two ural centra in the "urostyle." Garman (1899) described 22 species of ophidiid-brotulids from the eastern tropical Pacific, few of which have been retaken subsequently. However, the variety of kinds of ophidiid larvae in our material attests to a speciose fauna.

47. SCOMBRIDAE

(55 occurrences, 248 larvae)

Scombrid larvae were markedly less abundant in ETP II as compared with similar coverage on ETP I (163 occurrences, 1,840 larvae).

The majority of scombrid larvae from ETP II were those of *Auxis* sp. (34 occurrences, 151 larvae) or were too small to identify with certainty (30 occurrences, 84 larvae). The remaining scombrid larvae included the wahoo, *Acanthocybium solanderi* (Cuvier) (2 occurrences, 3 larvae) from Stations 45.065 and 46.004; the mackerel, *Scomber japonicus* Hottuyn, (2 occurrences, 4 larvae) from near the Galapagos Islands; bigeye tuna, *Thunnus obesus* Lowe, (1 occurrence, 1 larva); skipjack, *Katsuwonus pelamis* (Linnaeus), (2 occurrences, 2 larvae); yellowfin tuna, *Thunnus albacares* (Bonnaterre), (2 occurrences, 2 larvae). Scombrid larvae were given to W. Klawe of the Inter-American Tropical Tuna Commission for identification.

52. TRICHIURIDAE

(49 occurrences, 186 larvae)

In the ETP I contribution, I pointed out the similarity in appearance of larvae of *Diplospinus multistriatus* Maul and those of *Gempylus serpens*, and the problems this raised about the distribution of genera between Gempylidae and Trichiuridae and perhaps about the need for two families. Treating larvae of the two families separately in this paper was done only for convenience. The problems raised in the first ETP contribution still need to be solved.

Three kinds of trichiurid larvae were obtained on ETP II: larvae of *D. multistriatus* Maul, *Trichiurus lepturus* (L.), and *Lepidopus* sp.

The distribution of larvae of *D. multistriatus* (25 occurrences, 69 larvae) was strikingly similar on the two multivessel cruises (Figure 4 and Ahlstrom, 1971, Figure 14). On ETP II, all but two occurrences were in a compact group at the southern inner half of the ETP pattern between circa lat 8° and 15°S and offshore to long 95°W. Most ETP I collections of larvae of this species were obtained from this same

general area. The remaining two occurrences on ETP II were obtained at the northern, outer end of the pattern, again similar to the distribution of *Diplospinus* larvae on ETP I. On ETP II, there were no occurrences of *Diplospinus* larvae between these two widely separated groups; on ETP I two specimens were taken at intermediate localities. Larvae of this species have been obtained in a number of collections made in the North Pacific central water mass, with best distributional information from the NORPAC Expedition of August 1955. It is not taken in California Current waters, hence the distribution in the Humboldt Current waters off Peru does not have a mirror-image replication in the California Current, as has been found for a number of species.

Larvae of *Trichiurus lepturus* (20 occurrences, 106 larvae) were taken in a coastal band on ETP II (Figure 17). Eggs of this species are readily identified and occurred in many of the hauls containing *Trichiurus* larvae and in some additional hauls. Interestingly enough, larvae of this species were not obtained in ETP I collections, hence this is another exception to the general pattern of year-long reproduction by tropical pelagic fishes. Unlike larvae of *Gempylus* or *Nealotus*, which were widely distributed in the EASTROPAC area, larvae of this species appear to have a restricted, coastal distribution.

Larvae of *Lepidopus* sp. (3 occurrences, 9 larvae) were taken in contiguous stations at about lat 5°S off Peru (Figure 17). Larvae of *Lepidopus* were taken in more hauls on ETP I (7 occurrences, 25 larvae, Ahlstrom, 1971, Figure 14), all located between the equator and lat 5°N and offshore to long 92°W.

This change in area of spawning of *Lepidopus* from north of the equator on ETP I to the south of the equator on ETP II may not be significant, because of the paucity of positive hauls. If real, one can only surmise as to whether the two populations were discrete, with separate spawning seasons on the two sides of the equator.

53. BOTHIDAE

(70 occurrences, 690 larvae)

Bothid larvae occurred in more hauls than on ETP I (70 versus 56 occurrences) and in larger numbers (690 versus 199 larvae). The species composition, however, was similar (Table 22). A short section will be devoted to each of the forms listed in this table.

Bothus leopardinus (Günther)

(27 occurrences, 97 larvae)

Only larvae of *B. leopardinus* have been ob-

TABLE 22.—Frequency of occurrence and relative abundance of larvae of flatfishes, Pleuronectiformes, on the second multivessel EASTROPAC survey, summarized by vessel pattern.

Flatfish larvae	Washington 45,000 series		Undaunted 46,000 series		Rockaway 47,000 series		Total EASTROPAC II	
	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae
BOTHIDAE								
<i>Bothus leopardinus</i>	2	2	15	45	10	50	27	97
<i>Citharichthys-Etropus</i>	1	1	5	35	11	34	17	70
<i>Cyclosetta</i> sp.	0	0	4	26	9	12	13	38
<i>Engyophrys</i> <i>sancti-laurentis</i>	0	0	0	0	3	3	3	3
<i>Monolepis</i> sp.	0	0	0	0	1	1	1	1
<i>Syacium ovale</i>	6	15	17	201	32	264	55	480
Other Bothidae	1	1	0	0	0	0	1	1
Total Bothidae	7	19	28	307	35	364	70	690
CYNOGLOSSIDAE								
<i>Symphurus</i> spp.	2	5	16	109	38	248	56	362
Total Pleuronectiformes	7	24	30	416	46	612	83	1,052

tained in EASTROPAC collections. Although *B. mancus* (Broussonet) has been recorded from Clarion Island, off the west coast of Mexico (Norman, 1934), larvae of this species have not been obtained. Larval material of *B. mancus* has been examined from the vicinity of the Hawaiian Islands, and it differs from *B. leopardinus* in developing pigment on late stage larvae.

Larvae of *B. leopardinus* were distributed in a broad coastal band between Manzanillo, Mexico, and lat 4°N (Figure 8). This distribution is more restricted than that found on ETP I (Ahlstrom, 1971, Fig. 10). On ETP I, there were nine occurrences between lat 5°N and 6°S, as compared with a single occurrence on ETP II.

Citharichthys-Etropus

(17 occurrences, 70 larvae)

Although labeled *Citharichthys-Etropus* as for ETP I, the larvae taken on ETP II probably represent two species of *Citharichthys*, one with three elongated dorsal rays, the other with two elongated rays. Larvae of the latter were taken below the equator, either off Ecuador or near the Galapagos Islands (9 occurrences, 48 larvae). The form with three elongated dorsal rays was distributed in a coastal band between Manzanillo, Mexico, and Ecuador (8 occurrences, 22 larvae).

Cyclopsetta sp.

(13 occurrences, 38 larvae)

Larvae of *Cyclopsetta* sp. occurred in a broad coastal band between lat 15°N and circa lat 5°S. The larvae have been identified tentatively as *C. querna* (Jordan and Bollman). A developmental series was recently described by Guthertz (1970) for an Atlantic species of this genus, *C. fimbriata* (Goode and Bean). The Pacific and Atlantic species are similar in having opercular spination, a pair of sphenotic spines on the head, and nine or so elongated dorsal rays. They differ in several interesting respects. *C. fimbriata* transforms at a much smaller size, 14.0 mm, whereas the Pacific species can attain a length

of at least 32 mm before transformation. The opercular spination is more strikingly developed on the Pacific form, and the pelvic fins become markedly more elongate, extending almost to the base of the caudal fin, whereas the fins attain only about 40% of this length proportionately in *C. fimbriata*.

Engyophrys sancti-laurentii (Jordan and Bollman)

(3 occurrences, 3 larvae)

Only three larvae of this species were obtained on ETP II, two from the vicinity of the Gulf of Panama and one from near Puntarenas, Costa Rica.

Monolene sp.

(1 occurrence, 1 larva)

A 16-mm specimen was obtained at Station 47,520. Larvae of *Monolene* develop a single, prominent elongated dorsal ray (2nd fin ray)—this ray was 6 mm long. Its meristics—D.82, A.63, Vert. 39—would fit *Monolene asaedai* Clark (Perkins, 1963) and possibly *M. dubiosa* Garman. The other two eastern Pacific species, *M. maculipinna* Garman and *M. danae* Bruun, have higher fin ray counts. Morrow (1957b) reported taking a 65-mm larva of *M. maculipinna* off Peru in a pelagic trawl fishing to 152-fm depth over rather deep water (1,300 fm). Morrow's specimen had the following meristics: D.98, A.79, Vert. 43. *Monolene danae* Bruun (1937) was described from a juvenile taken in a pelagic trawl off Panama by the *Dana* in 1922.

Syacium ovale (Günther)

(55 occurrences, 480 larvae)

Although larvae of *S. ovale* were the most common bothid flatfish collected on both ETP I and ETP II, it was decidedly more abundant in ETP II as compared with ETP I (24 occurrences, 84 larvae). Larvae of *Syacium* occurred in a broad coastal band between Manzanillo, Mexico, and Ecuador (Figure 3); only three collections were obtained to the south of the

TABLE 23.—Familial composition of Lophiiform larvae taken on the second multivessel EASTROPAC survey, summarized by vessel pattern.

Family	Washington 45,000 series		Undaunted 46,000 series		Rockaway 47,000 series		Total EASTROPAC II	
	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae	No. positive hauls	No. larvae
Caulophryinae	0	0	2	2	0	0	2	2
Centrophrynidae	1	1	0	0	0	0	1	1
Ceratiidae	0	0	2	3	3	5	5	8
Gigantactinidae	8	9	5	5	5	13	18	27
Himantolophidae	4	5	1	1	3	3	8	9
Linophrynidae	2	2	0	0	19	32	21	34
Melanocetidae	3	3	13	18	17	23	33	44
Oneirodidae	11	11	13	18	23	53	47	82
Unidentified ceratioids	9	11	7	7	10	16	26	34
Antennariidae	0	0	1	1	0	0	1	1
Lophiidae	0	0	1	1	0	0	1	1
Total Lophiiform	25	42	33	56	56	145	114	243

equator. Most larvae of *Syacium* were under 5 mm in standard length, and few were as large as 9 mm. At the latter size, the adult complement of fin rays were present in all fins except the pectoral, and the vertebral column was completely ossified. The vertebral count in specimens examined was 10 + 25.

54. CYNOGLOSSIDAE

(56 occurrences, 362 larvae)

Larvae of *Symphurus* spp. were taken in a broad coastal band between Manzanillo, Mexico, and northern Peru. *Symphurus* larvae were taken in slightly less hauls than on ETP I (56 versus 63 occurrences), but in slightly larger numbers (362 versus 304 larvae). Two kinds of *Symphurus* larvae were widely distributed, and three or four additional kinds occurred sparingly. Of the two common forms, one developed two elongated dorsal rays and the other six elongated dorsal rays.

56. LOPHIIFORMES

(114 occurrences, 243 larvae)

Lophiiform larvae were accumulated during the identification and enumeration of ETP II larvae, and then studied as a unit. Ten families were represented (Table 23). All but two of the

specimens belonged to the subfamily Ceratioidei, a group of fishes whose ontogeny and taxonomy were dealt with in the impressive contribution of Bertelsen (1951). Ceratioid fishes have the most striking sexual dimorphism found in fishes. The males are parasitic in some ceratioids, free-living in others, but always quite small. Bertelsen showed that sex can be determined in the late larval stage; a papilliform illicium develops on the head of the female, but not on the male. A major achievement of Bertelsen was defining the distinguishing characteristics of larvae of all 10 ceratioid families. His work makes it possible to identify larger ceratioid larvae to the family level with assurance; however, small ceratioid larvae are much more difficult to identify because they have few distinguishing characters. Although Bertelsen worked out life history series to the generic or species level within all ceratioid families, ontogeny of the less common genera and species still remains unknown.

The ceratioids are a particularly difficult group in which to work out new developmental series. These cannot be based on larvae alone but must include transforming and adolescent specimens, preferably of both sexes, as well as adults. The EASTROPAC material, almost exclusively larvae, is inadequate for this purpose. Distributions of larvae are shown for five ceratioid families (Figure 18), as noted in the discussion of families. Most kinds of ceratioid larvae are quite rotund, hence aptly described as butterballs.

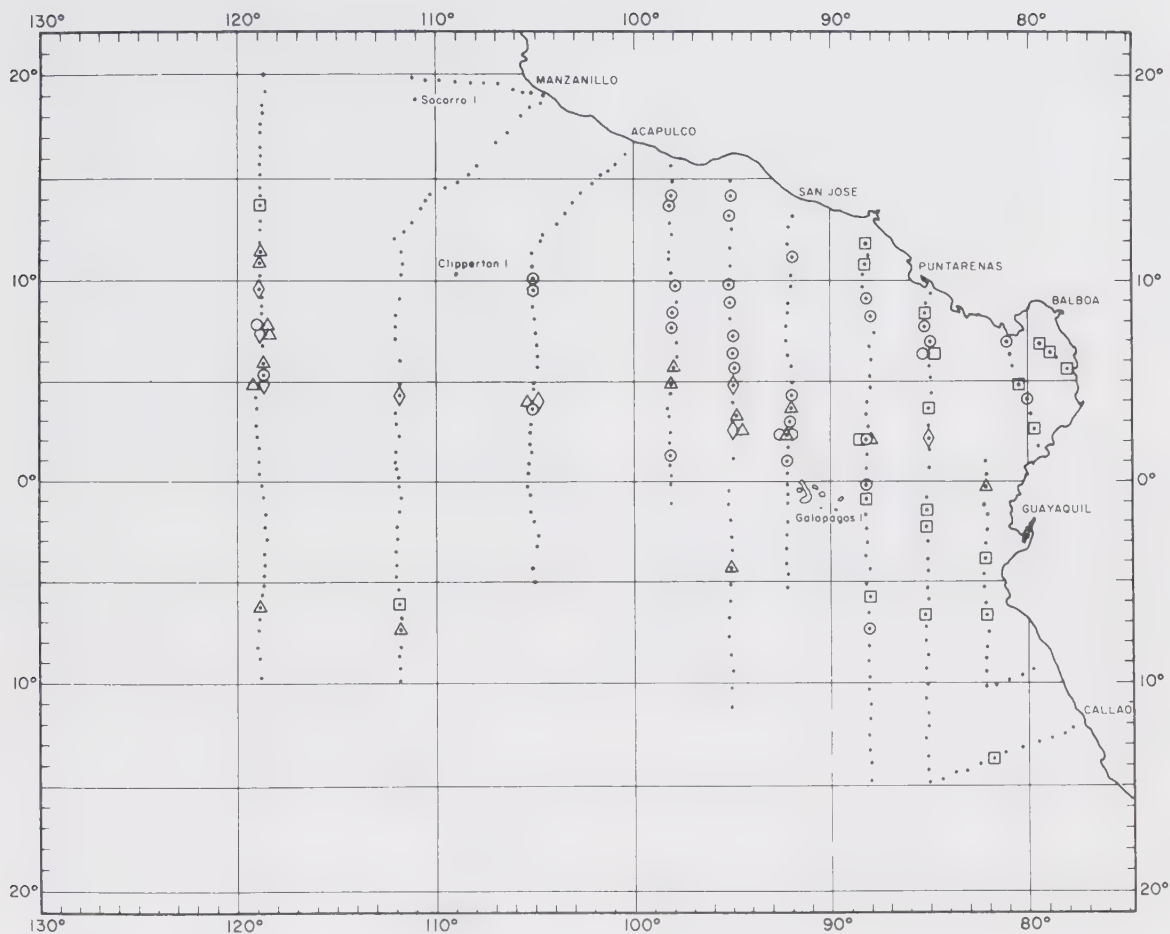


FIGURE 18.—Distribution of larvae of the lophiiform families Caulophryinae (*Caulophryne jordani*) (open hexagon with dot), Gigantactinidae (*Gigantactis* sp.) (open triangle with dot), Himantolophidae (*Himantolophus* sp.) (open diamond with dot), Linophryinae (2 or more genera represented) (open square with dot), and Melanocetidae (*Melanocetus* spp.) (open circle with dot); negative hauls are shown as small solid circles.

Caulophryinae

(2 occurrences, 2 larvae)

Bertelsen referred all material of Caulophryinae to a single species, *Caulophryne jordani* Goode and Bean. This is the only ceratioid fish known to develop pelvic fins. The two occurrences (Figure 18) were north of the equator in the pattern occupied by the middle vessel.

Centropryinae

(1 occurrence, 1 larva)

A single specimen was obtained of *Centropryne spinulosa* Regan and Trewavas in the off-shore pattern (Station 45.325). Larvae of this species develop a digitiform barbel on the throat, a character unique to the species.

Ceratiidae

(5 occurrences, 8 larvae)

Larvae were obtained of two species of Ceratiidae, *Cryptopsaras couesi* Gill and *Ceratias holboelli* Kroyer. Bertelsen had previously recorded larvae of *C. couesi* from the eastern tropical Pacific, but not of *C. holboelli*. Ceratiid larvae are peculiarly "humpbacked," and the larger larvae of females develop "caruncles" on their backs. The caudal ray count in ceratioid fishes is constant at nine, except for two species that develop only eight caudal rays—*C. couesi* is one of these.

Gigantactinidae

(18 occurrences, 27 larvae)

Larvae of *Gigantactis* sp. were taken in a triangular-shaped wedge, broadest offshore (Figure 18). Even small larvae of this family can be identified with certainty, because of the large size of the pectoral fins.

Himantolophidae

(8 occurrences, 9 larvae)

Larvae of Himantolophidae were taken to the north of the equator, between lat 2° and 10°N in all vessel patterns (Figure 18). Larvae are similar to Bertelsen's series for *Himantolophus groenlandicus* Reinhardt, and he recorded specimens from Panama. Two additional species of *Himantolophus* have been described from Panama or vicinity: *H. azuerlucens* Beebe and Crane and *H. rostratus* Regan. I have recorded the EASTROPAC larvae simply as *Himantolophus* sp.

Linophryinae

(21 occurrences, 34 larvae)

Several kinds of linophrynid larvae were taken, of which three were common—larvae of *Borophryne apogon* Regan, of the *Linophryne macrorhinus* group, and of the type designated

by Bertelsen as "*Hyaloceratis*." All but two occurrences of linophrynid larvae were in the inner pattern shoreward of the Galapagos Islands (Figure 18). Most linophrynid larvae are more elongate than other ceratioid larvae and also have the lowest D and A counts, usually D3 and A3.

Melanocetidae

(33 occurrences, 44 larvae)

At least two kinds of *Melanocetus* larvae were obtained on ETP II, with most specimens referable to *M. polyactis* Regan and the remainder to *M. johnsoni* Günther. Most records of *Melanocetus* were from the northeast quadrant of the EASTROPAC pattern (Figure 18).

Oneirodidae

(47 occurrences, 82 larvae)

At least one-third of the ceratioid larvae taken on ETP II were referable to the family Oneirodidae. Bertelsen (1951) recorded seven kinds of oneirodid larvae belonging to six genera from collections made off Panama. All but one of these were taken in ETP II, together with a new record for the eastern Pacific. Oneirodid larvae sampled on ETP II included *Chaenophryne draco*-group, *Chaenophryne longiceps*-group, *Dolopichthys* sp., *Micropolichthys microlophus* (Regan), *Oneirodes eschrichti*-group, *Oneirodes melanocauda* Bertelsen, and *Pentherichthys* sp. Bertelsen could identify some oneirodid larvae only to species groups, including the three listed above. Bertelsen included 24 nominal species in the *Oneirodes eschrichti*-group, most of which were possibly synonyms.

Perhaps the most interesting record of an oneirodid larva from ETP II was of *Oneirodes melanocauda* from Station 47.008, off Panama. A male, 9.5 mm TL (6.5 mm SL), agreed in all essential characters with Bertelsen's description. This is one of the more heavily pigmented ceratioid larvae. The fin counts were D6, A4, P19, C9. Bertelsen based his description of *O. melanocauda* on four specimens, 8 to 21 mm TL, the

largest a metamorphosing female. These were obtained in the South China Sea, Indian Ocean, and Caribbean Sea. The EASTROPAC record is the first from the Pacific.

The caudal fin is usually unpigmented in ceratioid larvae, but caudal pigment is developed on several kinds of oneirodid larvae. Larvae of *O. melanocauda* have stippled pigment near the outer margin of the caudal rays. Larvae of *Pentherichthys* sp. have pigment sprinkled over much of the caudal fin rays. A third kind of oneirodid larva with streaks of caudal pigment between the rays was taken at Station 47.250 (ontogenetic series yet to be worked out).

The larvae of *Pentherichthys* from the eastern Pacific are probably referable to *P. atratus* (Regan and Trewavas). Collections were made at six stations in the inner pattern between lat 2° and 8°N. The 10 specimens ranged in total length from 3.2 to 7.0 mm. Bertelsen remarked on the paucity of small specimens of *Pentherichthys* in the *Dana* material; only 2 of 19 specimens were under 7.5 mm in total length.

Antennariidae

(1 occurrence, 1 larva)

The specimen, taken at an inshore Station, 46.132, on the middle pattern, was 7.5 mm SL and had fin counts of D-II + I-13, A7, P10, V5, C9. These counts could apply equally to species in the genera *Histrio* or *Antennarius*.

Lophiidae

(1 occurrence, 1 larva)

A specimen of a lophiid larvae was obtained in the middle pattern at Station 46.145. This specimen, 15.5 mm SL (25.0 mm TL), had the following counts: D-II + I + III — 8, A6, P16/17, V6, C8. This specimen is referable to the genus *Lophiomus*. Garman described two species of *Lophiomus* from the eastern Pacific with identical counts to the above. Norman in his unpublished synopsis considered the genus monotypic with Garman's species as junior synonyms of *L. setigerus* Vahl. The third dorsal

spine is rather widely separated from an anterior group of two spines and a posterior group of three. The last ray in both the dorsal and anal fins was bifurcate to the base, differing in this respect from the last ray in ceratioid fishes, which is single. The larvae had two spines above the eye on either side of the head, differing in this character from the published larval series for *Lophius piscatorius* and *L. americanus* (Tåning, 1923); the pectoral fins were considerably smaller and compact.

57. OTHER IDENTIFIED

(23 occurrences, 51 larvae)

Two of the families, Amarsipidae and Stromateidae, have been discussed in the section dealing with Nomeidae and other Stromateioidae (No. 42). Other families included under "other identified" include Eutaeniophoridae (2 occurrences, 2 larvae), Gadidae (7 occurrences, 10 larvae), Callionymidae (2 occurrences, 2 larvae), Fistulariidae (1 occurrence, 1 larva), Gerridae-*Eucinostomus* sp. (4 occurrences, 15 larvae), Microdesmidae (4 occurrences, 6 larvae), Pomadasysidae-*Anisotremus* sp. (2 occurrences, 7 larvae), and Tetradontidae (1 occurrence, 1 larva).

ACKNOWLEDGMENTS

I wish to thank the many scientists who participated on EASTROPAC cruises for their care in collection and preservation of the plankton collections, and the technicians who laboriously sorted out fish eggs and larvae from the 1.0-m oblique plankton hauls for their thoroughness and patience. I especially wish to thank Elizabeth Stevens for her careful identification of the fish larvae obtained on the four EASTROPAC monitoring cruises made by the *David Starr Jordan*, Kenneth Raymond for preparing the distribution charts, Elaine Sandknop and Amelia Gomes for their aid in many aspects of the work, such as preparation of cleared and stained specimens and x-raying of juvenile and adult specimens. H. Geoffrey Moser worked closely in

studies of larvae of Myctophidae; W. L. Klawe identified the tuna larvae. I also wish to thank Daniel Cohen for his help in identifying juvenile specimens of *Brotula*, Michael Horn for his help in identifying specimens of Amarsipidae, Robert Wisner for his help in identification of the *Diaphus* fauna of the EASTROPAC area, and Solomon Raju for his help with eel leptocephali. I wish particularly to thank David Kramer, H. Geoffrey Moser, and Walter Matsu-moto for reviewing the manuscript.

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APPENDIX TABLE 1.—Counts of fish larvae, tabulated by family, for all stations occupied on the second multivessel EASTROPAC survey (EASTROPAC II).

STATION NUMBER	Myctophidae	Gonostomatidae	Sternoptychidae	Chauliodontidae	Idiacanthidae	Other Stomatoidei	Bathylagidae	Paralepididae	Scopelarchidae	Melamphidae	Bregmacerotidae	Exocoetidae	Trachypteridae	Apogonidae	Bramidae	Chiasmodontidae	Coryphaenidae	Nomeidae	Scombridae	Other identified larvae	Unidentified larvae	Disintegrated larvae	Total fish larvae
45.016	12	14	.	.	.	2	.	2	2	2	.	.	.	.	.	.	.	.	.	.	2	1	37
45.018	35	86	2	.	2	1	.	3	2	.	.	.	.	.	.	2	1	.	.	2	.	1	136
45.020	14	3	3	.	1	1	.	.	.	.	4	.	.	.	.	.	.	.	.	1	.	.	31
45.021	13	17	2	.	1	6	.	3	.	1	4	.	.	.	.	3	1	.	.	2	.	1	54
45.023	61	106	.	.	.	3	.	2	2	8	.	.	.	.	.	1	2	1	.	2	1	.	189
45.024	86	96	1	.	1	3	.	3	.	2	2	.	.	.	.	.	1	1	.	3	.	5	204
45.026	40	30	.	.	9	.	4	4	.	10	3	.	.	.	.	.	2	3	1	2	2	2	112
45.028	24	26	.	.	2	5	4	4	3	1	3	.	.	.	.	.	.	.	.	1	1	1	84
45.030	34	60	.	.	8	.	2	1	2	.	.	.	.	.	.	.	.	9	.	2	.	3	121
45.032	158	111	.	.	14	1	7	3	1	12	5	.	.	.	.	2	2	17	.	10	.	10	353
45.034	146	37	.	.	8	2	1	1	4	2	9	.	.	.	.	1	.	1	.	1	2	9	224
45.035	40	29	.	.	7	.	2	.	3	4	4	1	.	.	.	.	.	9	.	3	4	1	107
45.037	41	25	1	.	18	4	10	1	.	2	11	.	.	.	.	1	.	2	.	5	5	1	124
45.039	77	82	.	.	7	3	1	4	12	4	11	.	.	.	.	2	.	1	.	5	5	1	216
45.041	29	49	.	.	2	4	8	1	4	4	9	.	.	.	.	.	.	.	.	10	.	1	122
45.043	17	16	.	.	2	.	3	1	5	4	.	.	.	.	.	1	.	6	.	3	3	1	67
45.044	50	41	1	.	3	.	4	4	5	2	4	.	.	.	.	.	.	4	.	1	3	5	127
45.046	43	57	23	.	43	.	2	1	6	6	8	.	.	.	1	5	2	5	.	2	.	1	205
45.048	25	21	12	.	9	.	2	1	1	6	1	2	.	.	1	1	1	3	.	2	4	92	
45.050	19	3	6	.	1	.	1	2	.	2	.	.	.	.	.	.	.	1	.	2	.	1	40
45.051	87	15	14	.	.	.	4	1	.	.	1	.	.	.	.	.	1	.	.	2	.	3	125
45.053	75	19	31	.	.	.	2	.	3	11	.	.	2	1	.	.	.	.	.	4	.	3	151
45.054	44	3	16	1	.	.	1	.	4	24	.	.	1	.	.	.	.	.	.	1	1	1	97
45.056	22	6	20	.	.	.	1	.	2	23	.	1	.	.	.	2	1	.	5	.	7	90	
45.058	146	18	13	.	2	1	1	6	.	2	11	.	1	11	1	.	.	.	8	2	5	228	
45.060	82	4	2	.	3	3	1	3	2	5	29	.	1	13	1	.	.	1	.	3	2	7	168
45.063	29	46	2	.	2	14	1	3	.	.	9	.	10	2	2	2	2	.	6	1	9	138	
45.065	116	374	9	.	6	26	.	25	.	.	1	.	29	1	2	3	5	3	11	.	23	634	
45.067	185	584	37	4	2	48	3	56	.	.	.	.	1	12	3	.	1	5	1	31	3	11	992
45.071	42	40	7	.	.	3	.	5	.	.	2	.	.	11	1	.	1	3	.	5	.	1	121
45.073	65	68	14	.	.	2	2	5	.	.	1	.	.	22	.	.	.	3	.	4	1	16	203
45.078	71	107	10	.	.	.	1	6	2	.	3	.	.	3	1	.	.	4	.	2	.	2	212
45.083	37	26	13	.	.	1	.	5	.	1	.	.	.	11	.	.	2	4	.	1	.	4	105
45.086	65	77	2	1	.	2	3	9	5	3	.	.	.	1	.	.	.	2	.	.	.	21	191
45.090	47	67	3	1	.	3	8	5	.	.	.	.	.	.	.	1	.	2	.	6	.	12	156
45.094	150	107	12	.	.	3	6	27	.	.	1	.	.	2	.	2	1	2	.	.	.	33	346
45.098	43	16	3	.	.	.	2	1	.	1	.	.	.	1	.	.	1	.	.	.	.	10	85
45.102	136	32	12	.	.	3	1	24	.	7	.	.	.	2	.	1	.	1	.	1	.	16	288
45.106	265	21	21	.	.	2	5	4	1	3	.	1	.	.	.	1	.	2	.	1	3	22	354
45.110	545	32	188	.	.	5	12	5	1	4	.	.	.	.	.	7	.	5	.	4	.	9	817
45.114	40	20	51	.	.	.	2	2	.	1	.	.	.	.	.	.	.	5	.	.	1	16	138
45.117	92	49	86	.	.	.	1	4	.	2	.	.	.	.	.	.	.	6	.	2	1	20	263
45.121	55	98	209	.	.	.	4	3	.	2	.	.	.	.	1	.	.	.	.	2	.	25	399
45.125	41	325	34	.	.	.	.	1	.	1	.	.	.	.	.	1	.	6	.	2	.	416	
45.127	21	39	31	.	.	.	.	.	.	6	.	.	.	7	2	.	.	.	.	3	3	10	122
45.129	22	3	24	.	.	.	.	.	.	4	.	.	.	3	.	.	.	.	.	.	1	6	63
45.131	73	337	23	.	.	.	.	.	.	2	.	.	.	.	2	1	.	2	.	3	4	25	472
45.133	323	33	23	.	9	4	.	5	5	.	7	.	.	.	.	.	.	.	1	3	.	3	416
45.135	165	17	19	.	2	.	.	2	1	.	3	2	.	.	.	.	.	.	1	1	4	10	227
45.137	11	.	12	1	.	.	.	1	2	.	.	.	.	.	.	.	.	.	.	.	.	.	27
45.139	24	2	3	1	.	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	3	36
45.146	106	87	49	8	.	.	.	11	10	1	.	.	.	.	.	.	.	.	.	2	20	44	338

APPENDIX TABLE 1.—Counts of fish larvae, tabulated by family, for all stations occupied on the second multivessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	Myctophidae	Gonostomatidae	Sternoptychidae	Chauliodontidae	Idiacanthidae	Other Stomatoidae	Bathylagidae	Paralepididae	Scopelarchidae	Melamphidae	Bregmacerotidae	Exocoetidae	Trachypteridae	Apogonidae	Bramidae	Chlasmodontidae	Coryphaenidae	Nomidae	Scombridae	Other identified larvae	Unidentified larvae	Disintegrated larvae	Total fish larvae
45.163	8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	8
45.165	152	65	212	1	6	3	.	1	4	2	8	.	.	.	.	.	.	.	.	3	2	12	471
45.167	86	6	10	.	.	.	.	.	2	2	.	.	.	.	.	.	.	1	.	.	.	10	119
45.169	56	15	1	.	.	.	.	1	.	.	.	.	.	1	.	.	.	.	.	.	.	8	82
45.171	26	1	12	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	9
45.173	10	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	9	50
45.175	62	27	29	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	13
45.177	70	146	46	.	.	.	.	5	.	.	.	.	.	1	1	.	1	.	2	.	3	127	
45.179	59	33	8	.	.	.	.	1	1	1	.	.	.	.	.	.	.	1	.	3	.	1	281
45.183	26	14	70	.	.	.	4	4	2	.	.	.	.	.	.	.	1	.	.	.	.	9	113
45.187	255	14	87	.	.	.	16	3	2	.	.	.	.	.	.	.	.	.	1	.	.	2	123
45.191	144	15	80	.	.	.	5	17	5	.	.	.	.	.	.	.	.	.	3	.	.	2	382
45.194	49	4	40	.	.	.	3	11	1	.	.	.	.	.	.	1	.	.	1	.	.	4	272
45.198	251	21	31	.	.	3	7	22	1	.	.	.	.	.	.	1	.	1	.	.	.	4	113
45.202	53	19	5	.	.	1	2	9	1	.	.	.	.	.	.	.	.	.	.	2	.	11	350
45.206	22	3	1	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	92
45.283	102	13	7	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	30
45.287	25	82	1	.	.	.	2	3	.	.	.	.	.	.	.	.	.	.	2	.	.	3	129
45.289	157	125	1	.	.	.	2	16	1	.	.	.	.	.	.	1	.	.	.	1	.	2	114
45.293	157	58	13	.	2	4	4	11	1	2	2	.	1	2	1	1	.	.	2	2	2	306	
45.297	231	107	14	.	1	15	7	17	2	6	11	.	.	19	.	1	.	.	.	.	1	8	440
45.301	24	26	13	.	.	4	8	5	.	3	.	.	1	2	.	1	1	1	.	4	.	.	93
45.305	119	1040	17	.	1	3	2	.	1	1	6	.	1	.	.	1	6	10	.	1	.	9	1217
45.309	44	150	22	1	1	8	.	4	1	1	2	.	.	3	.	3	2	.	2	.	7	251	
45.313	49	35	5	.	1	4	2	6	.	2	.	.	.	4	.	.	1	.	1	.	.	9	119
45.316	41	34	8	1	.	3	1	2	.	1	4	.	.	.	1	.	.	.	1	.	2	99	
45.319	32	46	17	.	.	2	.	3	.	3	4	.	.	1	.	.	.	.	2	.	1	111	
45.321	45	13	20	.	.	.	2	.	.	7	4	.	.	.	.	.	.	.	1	1	1	94	
45.323	51	4	1	.	.	3	1	2	.	7	1	.	.	.	.	1	.	.	1	1	1	74	
45.325	1002	28	19	.	1	.	42	3	1	7	1	.	1	.	6	.	1	8	1	4	.	3	1128
45.329	69	4	11	.	8	.	3	1	.	3	.	1	.	.	1	.	1	4	.	1	.	3	110
45.331	235	5	11	.	1	1	13	.	.	6	3	.	.	.	1	.	.	10	.	1	2	1	290
45.333	108	28	10	.	.	2	5	1	.	4	3	1	.	.	.	.	1	25	.	13	.	.	201
45.335	65	32	2	.	14	5	8	3	3	1	1	.	.	.	.	.	1	9	.	8	1	2	155
45.337	49	12	6	.	21	12	1	3	1	12	6	.	.	.	.	2	2	14	.	1	.	16	158
45.339	26	8	.	.	15	4	2	.	.	7	8	1	.	.	.	3	1	5	.	9	2	9	100
45.341	47	70	.	.	7	1	3	4	4	3	2	.	.	.	.	.	1	1	.	1	.	.	144
45.343	17	32	.	.	8	1	2	2	.	2	2	3	.	.	.	.	1	4	.	2	.	1	77
45.344	21	37	.	.	6	2	1	3	1	3	3	1	1	.	.	.	1	11	.	4	.	4	99
45.346	19	19	.	.	2	1	.	4	.	3	2	.	.	.	.	.	1	4	.	2	.	1	58
45.348	30	120	.	.	3	.	.	4	4	.	.	.	.	.	.	.	.	2	.	3	.	.	166
45.350	70	297	.	.	1	2	.	1	.	.	.	.	.	.	.	.	.	6	.	1	.	5	383
45.352	29	66	.	.	.	.	3	2	.	1	1	1	.	.	.	.	.	3	.	.	.	10	116
45.356	69	153	.	.	5	.	11	6	1	1	.	3	.	.	.	.	2	19	9	1	2	.	282
45.358	98	107	.	.	1	.	1	.	.	4	2	4	1	.	.	.	1	6	5	2	3	7	242
45.360	18	37	.	.	.	1	7	2	.	1	.	.	.	.	.	.	9	5	4	3	4	91	
45.362	36	31	.	.	.	.	6	8	.	4	2	.	.	.	.	.	1	8	6	17	8	1	128
45.365	99	55	.	.	.	.	1	1	.	.	27	.	.	.	.	.	.	.	4	103	15	6	311
45.367	23	10	.	.	1	1	7	1	.	.	3	.	.	.	.	.	.	.	.	19	.	73	138
45.369	101	106	.	.	.	2	3	10	1	2	25	.	.	.	.	.	1	7	12	61	11	15	357
45.371	120	239	.	.	1	2	13	4	3	10	13	.	1	.	.	.	.	7	6	10	6	11	446
45.373	117	149	.	.	1	.	14	1	.	2	.	2	.	.	.	.	.	13	9	10	3	.	321

APPENDIX TABLE 1.—Counts of fish larvae, tabulated by family, for all stations occupied on the second multivessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	Myctophidae	Gonostomatidae	Sternoptychidae	Chauliodontidae	Idiacanthidae	Other Stomiatoidei	Bathylagidae	Paralepididae	Scopelarchidae	Melamphatidae	Bregmaceroiidae	Exocoetidae	Trachypteridae	Apogonidae	Bramidae	Chiasmodontidae	Coryphaenidae	Nomeidae	Scombridae	Other identified larvae	Unidentified larvae	Disintegrated larvae	Total fish larvae	
45.375	34	39	.	.	.	1	3	1	.	1	2	2	.	.	.	.	.	2	.	4	.	2	91	
45.377	67	86	.	.	.	2	8	3	1	3	1	.	.	.	.	.	2	18	6	11	.	18	226	
45.379	179	805	.	.	.	1	2	6	2	3	3	1	.	.	.	.	.	3	.	10	12	1	1048	
45.381	98	246	.	.	1	.	4	3	.	4	3	.	.	.	.	.	.	2	.	3	2	5	371	
45.383	40	20	.	.	.	.	4	.	.	4	.	.	.	.	.	.	.	.	.	2	5	3	78	
45.385	19	60	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	2	83	
45.387	26	429	.	.	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	461	
CRUISE	46																							
46.002	14	19	.	.	.	.	2	1	.	.	.	2	.	.	.	.	1	14	.	2	2	1	58	
46.004	103	122	.	.	11	3	4	18	2	5	3	.	.	.	.	.	7	21	2	3	2	3	309	
46.006	30	19	.	.	5	1	1	2	.	1	5	.	1	.	.	1	.	9	.	1	4	1	81	
46.007	10	26	.	.	1	.	.	2	.	4	1	.	.	.	.	.	14	.	.	1	.	6	67	
46.009	17	23	.	.	2	.	1	2	.	.	1	.	.	1	.	.	2	8	.	2	.	3	62	
46.011	60	72	.	.	4	2	1	5	3	5	1	1	.	.	.	1	3	16	.	2	1	.	177	
46.013	89	51	.	.	2	5	.	2	5	1	2	.	.	.	.	.	1	7	.	1	.	.	166	
46.015	12	17	.	.	2	.	1	11	.	4	7	.	.	.	.	.	1	8	.	1	.	.	70	
46.017	25	4	.	.	11	.	.	.	1	1	9	.	.	.	.	.	2	1	.	2	1	.	62	
46.019	285	148	.	.	17	2	1	2	9	1	9	.	1	1	.	.	2	.	.	3	.	.	481	
46.020	160	80	.	.	16	2	10	3	4	2	2	1	.	.	.	.	2	1	1	.	1	.	285	
46.022	38	14	11	.	4	.	1	2	1	8	1	2	.	.	1	1	1	8	3	1	1	2	100	
46.024	64	27	2	.	3	1	5	1	3	2	2	1	.	.	2	.	.	7	1	2	2	.	125	
46.026	206	140	2	.	2	.	5	6	4	11	3	1	.	1	.	4	.	13	3	.	2	.	403	
46.028	412	157	10	.	9	2	12	6	1	10	4	.	.	.	1	3	15	2	2	1	8	.	655	
46.030	85	7	12	.	3	2	8	.	.	2	2	.	.	.	.	.	1	2	.	.	.	7	131	
46.032	9	.	3	.	.	.	1	.	.	.	.	.	.	.	.	1	.	1	.	1	.	.	21	
46.034	152	40	17	1	.	3	5	3	1	1	9	.	.	.	1	1	1	1	.	7	2	2	248	
46.036	436	127	28	.	2	1	7	8	1	4	4	1	.	1	.	1	3	.	1	3	.	6	634	
46.038	20	7	10	.	.	.	3	1	1	2	.	1	.	.	.	.	.	1	.	.	.	3	49	
46.040	25	29	8	.	.	1	.	4	.	1	.	.	.	1	2	.	.	.	.	3	.	4	69	
46.042	62	133	5	.	1	.	4	.	.	2	1	2	.	1	.	.	.	.	1	1	1	4	218	
46.044	89	96	21	.	.	1	1	1	.	5	1	1	.	1	.	.	.	1	.	1	2	11	232	
46.046	78	57	22	.	.	2	1	2	3	3	.	.	.	2	1	.	.	.	1	8	.	11	191	
46.048	63	54	24	.	1	.	10	3	.	5	4	1	.	4	1	.	1	.	.	3	3	4	181	
46.050	250	184	15	.	.	1	12	24	1	7	11	.	.	11	1	1	4	.	3	4	15	547		
46.052	319	217	25	.	3	.	7	18	1	3	4	.	.	11	1	.	1	2	.	13	3	5	631	
46.054	211	181	22	.	.	3	20	23	1	6	9	.	.	.	.	2	.	.	.	2	3	14	497	
46.055	109	73	10	.	1	1	5	18	4	4	4	.	.	3	3	4	.	3	.	.	.	16	249	
46.057	751	549	5	.	.	2	10	70	2	3	.	.	.	2	.	3	.	3	.	6	2	.	1506	
46.059	494	504	.	.	.	5	2	59	2	1	1	.	.	.	.	1	.	2	.	22	.	5	1098	
46.061	148	98	5	1	.	1	3	23	.	1	.	.	.	.	.	.	.	.	.	14	.	72	366	
46.063	48	19	6	3	.	.	2	10	.	.	.	.	.	.	.	.	.	1	.	.	5	20	116	
46.065	404	97	14	.	.	5	4	50	.	2	.	.	.	.	.	6	.	.	.	2	.	8	592	
46.067	269	121	20	.	.	2	5	14	.	1	.	.	.	.	.	.	.	.	.	2	3	20	461	
46.069	116	59	23	.	.	.	22	53	.	4	.	.	.	.	.	.	.	.	.	5	33	20	331	
46.071	77	27	34	.	.	.	14	22	.	.	.	.	.	.	.	.	.	.	.	.	4	3	16	192
46.075	35	21	32	.	.	.	5	17	.	4	.	.	.	.	.	.	.	.	.	.	.	.	6	120
46.077	36	19	12	.	.	1	1	3	.	1	.	.	1	1	.	1	.	.	.	3	.	.	79	
46.079	408	30	14	.	.	22	23	31	.	2	.	.	.	.	.	.	.	1	.	4	.	1	536	
46.082	61	46	13	.	.	5	17	15	.	2	.	.	.	.	.	.	.	1	.	8	.	8	176	

APPENDIX TABLE 1.—Counts of fish larvae, tabulated by family, for all stations occupied on the second multivessel EASTROPAC survey (EASTROPAC II).—Continued

STATION NUMBER	Myctophidae	Gonostomatidae	Sternopterygidae	Chauliodontidae	Idiacanthidae	Other Stomatolidae	Bathylagidae	Paralepididae	Scopelarchidae	Melamphidae	Bregmaceroidae	Exocoetidae	Trachypteridae	Apogonidae	Bramidae	Chiasmodontidae	Coryphaenidae	Nomeidae	Scombridae	Other identified larvae	Unidentified larvae	Disintegrated larvae	Total fish larvae
46.084	45	39	13	.	.	2	21	21	.	3	.	.	.	.	.	.	.	.	.	6	1	8	159
46.086	102	233	25	.	1	2	33	26	.	3	.	.	.	.	.	.	.	4	.	8	.	1	443
46.088	124	60	16	.	.	6	8	27	.	.	.	.	.	.	.	.	.	3	.	4	1	9	258
46.090	99	24	47	.	1	4	4	24	3	6	.	.	.	.	.	1	.	7	.	.	.	143	369
46.092	100	29	36	.	.	4	3	10	2	4	.	.	.	1	.	.	1	4	.	.	4	2	200
46.094	300	156	87	.	2	7	3	21	.	5	3	.	2	.	.	1	.	.	.	3	1	1	595
46.096	240	249	54	.	3	2	13	24	1	5	3	3	.	7	.	.	3	2	.	7	8	4	628
46.098	73	42	35	.	.	8	2	4	.	3	.	.	.	7	1	1	.	1	.	2	3	15	197
46.100	125	6	41	.	3	.	2	1	3	2	9	.	.	.	.	.	.	.	.	1	1	6	202
46.102	334	56	67	1	1	4	3	10	.	9	7	.	.	1	.	2	.	.	.	4	3	4	508
46.104	109	46	36	1	2	4	.	10	1	1	.	.	.	2	.	.	.	1	2	.	2	12	232
46.106	115	41	19	.	.	1	9	1	.	2	.	1	1	.	.	.	2	7	1	2	4	4	210
46.108	250	36	45	.	.	7	27	.	.	.	.	.	.	.	.	.	.	20	4	5	1	18	415
46.110	162	10	22	.	1	.	5	.	5	3	.	1	.	.	.	.	.	2	3	15	1	.	230
46.112	562	75	14	.	1	1	16	3	.	.	.	.	.	.	.	.	.	3	14	49	.	.	738
46.114	31	5	2	.	1	1	3	.	2	.	3	2	.	.	.	.	.	3	.	7	.	.	61
46.116	14	5	3	.	1	.	.	1	.	3	.	.	.	.	.	.	.	7	.	1	.	2	37
46.118	176	85	6	.	4	1	3	7	2	5	1	1	1	.	.	.	4	13	.	1	4	3	321
46.120	80	109	.	.	13	2	1	9	1	1	2	1	3	.	.	.	2	12	.	10	.	.	237
46.122	17	29	.	.	2	2	4	4	2	2	3	.	1	.	.	.	1	10	.	8	.	.	85
46.124	19	22	.	.	.	.	2	3	1	4	3	.	.	.	.	.	1	12	.	6	3	3	79
46.126	63	98	.	.	13	1	10	7	1	7	1	1	1	.	.	.	.	4	.	20	10	.	237
46.128	113	131	.	.	11	7	.	11	2	9	19	.	.	.	.	.	1	12	.	7	7	3	343
46.130	46	55	.	.	1	5	11	6	1	6	10	.	.	.	.	.	1	9	.	5	20	9	183
46.132	26	26	.	.	.	.	5	9	.	.	4	.	.	.	.	.	.	17	11	12	19	1	130
46.134	9	12	.	.	3	.	8	.	.	511	.	.	.	.	.	.	2	.	20	93	18	8	684
46.135	81	12	.	.	1	.	3	.	.	927	.	.	.	.	.	.	1	5	6	149	24	4	1218
46.137	201	24	1	.	1	1	24	.	.	7	9	.	.	.	.	.	.	4	.	278	.	7	561
46.139	175	52	1	.	1	.	11	1	1	6	1	.	.	.	.	.	.	15	3	15	.	1	283
46.141	438	20	4	1	1	2	18	1	1	4	.	4	1	.	2	.	1	6	.	8	3	3	518
46.143	113	15	30	.	1	.	10	.	1	2	1	.	.	.	1	.	.	7	1	3	2	5	201
46.145	262	119	24	.	3	2	37	3	.	2	.	.	1	.	.	.	2	4	2	4	2	1	489
46.147	484	41	49	.	2	1	41	1	3	4	.	.	.	.	.	.	.	5	1	4	.	6	642
46.149	1333	14	30	.	1	10	27	.	.	7	1	.	.	.	.	.	.	6	.	4	2	2	1432
46.151	1358	9	24	.	1	4	13	.	.	8	.	.	.	.	.	2	.	.	.	1	.	.	1420
46.153	2561	165	81	.	2	3	4	.	1	7	.	1	1	.	.	.	.	4	.	18	.	16	2864
46.155	273	146	67	.	4	4	6	1	.	8	1	.	.	.	2	1	2	3	3	11	.	3	1234
46.157	490	27	76	1	1	7	6	5	1	8	3	.	1	7	2	.	2	.	.	7	2	12	660
46.159	71	11	32	.	.	2	7	1	.	2	.	.	.	3	1	.	2	.	.	6	.	1	134
46.161	350	47	73	.	4	7	8	12	2	15	.	.	.	.	.	1	.	.	1	12	1	3	531
46.163	290	83	64	.	7	4	1	12	1	13	.	.	1	1	.	.	.	.	.	6	2	41	540
46.165	90	36	60	.	5	.	18	15	.	7	.	3	1	1	.	1	1	.	.	9	5	9	261
46.167	195	40	49	.	3	1	37	7	.	11	.	.	2	2	.	.	.	5	.	7	2	25	386
46.169	163	236	30	.	.	4	52	46	.	10	.	1	.	.	.	2	.	1	.	4	4	10	563
46.171	255	55	15	.	1	3	44	28	.	7	.	.	.	.	.	.	.	.	.	72	.	60	545
46.173	33	15	6	.	.	.	10	6	.	1	.	.	.	.	.	.	.	.	.	5	.	2	78
46.175	52	76	4	.	1	.	21	3	.	2	.	.	.	.	.	.	.	.	.	.	.	1	162
46.177	124	33	17	.	1	2	45	16	.	10	.	.	.	.	.	.	.	.	1	26	.	6	281
46.179	213	110	54	.	1	4	135	19	.	22	.	.	.	.	.	.	.	.	3	110	3	14	688
46.181	52	58	13	3	2	.	132	13	.	14	.	.	.	.	.	.	.	1	.	21	18	4	339
46.183	85	21	29	2	4	11	47	11	1	9	2	.	.	.	.	2	.	2	.	5	.	4	235
46.185	262	97	54	.	2	10	45	12	.	9	.	.	.	.	.	3	.	2	.	6	.	3	505

APPENDIX TABLE 1.—Counts of fish larvae, tabulated by family, for all stations occupied on the second multivessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	Myctophidae	Gonostomatidae	Sternopychidae	Chauliiodontidae	Idiacanthidae	Other Stomatoidel	Bathylagidae	Paralepididae	Scopelarchidae	Melamphidae	Bregmaceroidae	Exocoetidae	Trachypteridae	Apogonidae	Bramidae	Chiasmodontidae	Coryphaenidae	Nemidae	Scombridae	Other identified larvae	Unidentified larvae	Disintegrated larvae	Total fish larvae
46.187	516	42	23	.	1	1	17	7	2	2	.	.	.	.	1	.	.	2	.	6	3	6	629
46.189	236	5	19	1	.	1	3	.	1	4	.	.	.	.	.	.	.	.	.	1	1	1	278
CRUISE	47																						
47.001	97	63	6	.	.	.	4	2	.	2	15	.	.	.	1	.	1	1	.	42	.	.	234
47.005	287	206	21	.	3	.	6	6	1	8	22	.	.	1	.	.	1	2	.	81	6	17	668
47.008	257	49	5	.	9	2	7	2	3	13	4	.	.	.	.	.	.	.	.	70	1	7	429
47.011	161	26	4	.	2	1	3	1	1	5	21	.	.	.	.	.	2	.	.	32	2	2	263
47.019	370	234	2	.	.	.	5	8	.	3	.	.	.	2	1	.	.	.	145	63	10	843	
47.022	169	29	26	.	1	5	3	.	.	.	.	.	.	.	.	.	.	3	.	17	2	10	265
47.025	83	58	5	.	3	1	4	3	.	.	4	1	.	.	.	.	.	1	.	10	1	2	176
47.028	264	118	40	.	16	.	14	15	2	9	5	.	.	.	.	.	1	1	.	52	15	10	562
47.032	208	141	72	.	4	2	15	10	2	8	5	.	1	.	1	.	1	7	.	22	2	8	509
47.034	139	36	8	.	3	1	7	27	.	3	5	.	.	.	1	.	.	2	.	45	7	18	302
47.035	223	73	23	.	16	2	20	43	.	11	7	1	.	.	.	.	4	.	29	1	10	463	
47.040	205	85	29	.	5	2	8	24	.	4	34	.	.	.	.	.	1	3	.	127	18	22	567
47.049	64	107	20	.	1	8	26	50	.	6	2	.	.	.	.	.	1	11	.	12	2	35	347
47.053	265	102	9	.	2	6	27	27	.	12	.	.	1	.	.	.	.	17	.	82	7	21	580
47.057	300	116	5	.	.	13	50	29	.	11	.	1	.	.	1	.	2	33	.	114	6	50	731
47.061	79	20	9	1	.	4	11	17	.	7	22	.	.	.	.	3	.	12	.	33	4	9	231
47.065	99	93	7	.	.	11	30	5	.	4	8	54	.	.	.	.	.	8	.	22	5	19	365
47.069	140	51	64	.	.	3	143	10	.	5	.	.	.	.	1	1	3	.	1	38	6	9	480
47.070	90	14	13	.	.	11	188	8	.	.	.	.	.	.	.	1	.	5	.	34	2	.	370
47.074	138	14	19	.	1	8	301	5	.	.	.	.	.	.	.	.	.	2	.	65	11	23	587
47.078	11	5	5	.	.	.	64	2	.	.	.	.	.	.	.	.	.	.	.	9	.	6	102
47.082	119	6	13	.	.	.	80	7	.	.	.	.	.	.	.	.	.	.	.	29	1	2	257
47.086	248	11	59	.	.	.	530	.	3	2	.	.	.	.	.	.	.	.	127	2	20	1002	
47.090	57	5	6	.	1	2	83	.	.	.	.	.	.	.	.	.	.	.	3	.	5	162	
47.094	100	2	17	.	.	.	8	.	1	.	.	.	.	.	.	.	.	.	1	.	3	132	
47.097	16	.	6	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	258	1	1	283	
47.099	16	.	2	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	62	.	2	84	
47.101	48	.	1	.	2	.	1	.	.	2	.	.	.	.	.	.	.	.	227	.	1	282	
47.103	2	.	4	2	1	1	2	.	.	.	.	.	.	.	.	.	.	.	2	.	1	15	
47.105	4	5	1	.	.	.	5	.	.	2	.	.	.	.	.	.	.	.	4	.	.	21	
47.107	109	7	1	.	.	.	4	.	.	4	.	.	.	.	.	.	.	.	9	.	.	134	
47.109	6	.	1	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	293	.	4	305	
47.113	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	35	.	2	38	
47.124	10	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	99	.	1	110	
47.128	35	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	96	6	.	137	
47.132	85	9	1	7	.	.	3	.	3	4	.	.	.	.	.	.	.	.	46	.	.	158	
47.134	21	9	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	20	.	.	52	
47.137	17	12	4	.	.	.	3	.	2	5	1	.	.	.	.	1	.	.	1	.	2	48	
47.139	16	11	.	2	.	.	5	.	.	4	.	.	.	.	.	.	.	.	9	.	.	47	
47.141	24	17	.	4	.	.	13	.	2	3	.	.	.	.	.	.	.	.	18	.	9	90	
47.143	23	2	1	26	4	.	16	.	.	1	.	.	.	.	.	.	.	.	4	3	9	89	
47.145	15	14	1	4	1	.	5	.	3	3	1	.	.	.	.	3	.	.	.	.	2	52	
47.147	44	78	3	13	2	1	16	.	.	.	3	.	.	.	2	4	.	.	5	1	4	181	
47.149	40	28	3	7	.	4	15	.	.	3	1	.	.	.	.	6	.	.	3	1	8	119	
47.151	22	3	.	.	.	.	4	.	.	1	2	.	.	.	.	1	.	.	6	.	11	50	
47.153	30	13	.	.	.	1	17	.	5	5	1	.	.	.	.	9	.	.	6	8	5	100	

APPENDIX TABLE 1.—Counts of fish larvae, tabulated by family, for all stations occupied on the second multivessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	Myctophidae	Gonostomatidae	Sternopterygidae	Chauliodontidae	Idiacanthidae	Other Stomatoidae	Bathylagidae	Paralipidae	Scopelarchidae	Melamphidae	Bregmaceroidae	Exocoetidae	Trachypteridae	Apogonidae	Bramidae	Chasmodontidae	Coryphaenidae	Nomeidae	Scombridae	Other identified larvae	Unidentified larvae	Disintegrated larvae	Total fish larvae
47.155	.	3	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4
47.157	109	77	8	16	3	.	27	.	1	2	1	.	.	.	.	11	.	.	.	8	3	8	274
47.159	17	11	.	7	.	.	14	.	1	5	.	1	.	.	.	.	.	.	.	1	1	4	62
47.162	11	5	.	.	.	.	6	.	.	3	.	.	.	.	.	.	.	1	.	2	.	1	29
47.164	25	37	.	1	.	.	10	.	.	12	.	.	.	.	.	.	.	2	.	2	.	5	94
47.166	28	21	4	.	.	.	1	.	1	3	.	.	3	.	.	1	.	2	.	.	.	.	64
47.168	6	1	1	.	.	.	3	.	1	3	.	.	.	.	1	3	.	1	.	1	3	3	27
47.171	66	39	15	.	.	.	9	.	.	4	.	.	.	.	.	.	.	8	.	.	1	4	149
47.173	251	166	31	.	.	.	17	.	6	3	.	.	.	.	.	.	23	.	2	.	.	11	518
47.175	327	95	4	2	.	.	16	.	1	.	.	.	.	.	.	.	.	5	.	15	1	.	470
47.177	119	100	10	.	.	69	157	4	1	1	.	.	.	.	.	.	.	19	.	12	.	40	532
47.179	228	14	1	.	2	11	189	.	3	2	.	.	.	.	.	1	.	3	.	3	.	42	499
47.181	150	32	7	1	.	12	59	.	1	.	.	.	.	.	.	.	.	.	.	11	.	3	276
47.185	350	31	45	1	3	12	140	23	4	5	.	.	.	.	.	2	.	1	.	27	.	14	658
47.189	28	5	8	.	.	.	8	97	3	1	4	.	.	.	.	.	.	.	.	5	.	26	185
47.193	2	2	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	6
47.197	97	9	13	.	2	23	123	4	.	5	.	.	.	.	.	1	.	2	.	17	2	8	306
47.201	392	152	24	.	1	12	140	20	.	10	.	.	.	.	.	9	.	2	.	8	.	54	824
47.205	109	48	27	.	.	23	152	20	.	17	1	1	.	.	1	2	.	4	.	8	3	125	541
47.213	769	443	43	.	14	3	58	26	.	25	.	2	2	.	.	.	.	43	.	43	5	40	1513
47.217	440	90	44	.	.	4	30	20	.	4	.	1	.	.	.	.	.	5	.	20	.	11	677
47.221	452	36	54	.	13	2	30	43	.	9	.	.	.	.	.	2	1	3	.	17	.	14	676
47.225	512	151	53	.	5	7	34	31	5	6	2	.	2	1	1	.	4	15	.	16	2	13	860
47.229	496	272	83	.	14	5	17	11	1	9	2	.	1	.	.	1	1	5	.	21	.	3	942
47.233	1441	249	95	2	42	6	14	31	5	18	2	1	1	.	2	1	3	3	1	16	5	37	1975
47.237	100	17	18	.	4	.	8	2	1	3	.	.	.	.	.	.	1	1	.	7	.	3	165
47.240	201	46	51	.	5	.	3	3	.	1	.	2	.	.	2	1	3	16	.	13	.	1	348
47.242	953	94	18	.	2	2	20	3	.	6	9	.	.	.	.	2	.	8	1	14	.	6	1138
47.244	905	129	16	.	1	7	22	.	2	5	2	.	1	.	.	1	3	12	1	26	2	.	1135
47.246	111	8	6	.	.	1	2	.	.	1	.	.	.	.	.	.	1	12	.	4	.	2	148
47.250	297	18	.	.	.	6	3	.	.	.	1	.	.	.	.	.	.	5	.	15	3	1	349
47.254	245	27	11	.	1	2	3	1	.	3	2	.	.	.	.	1	.	8	.	15	2	.	326
47.258	516	38	6	.	.	.	3	.	.	.	9	.	.	.	.	.	1	6	1	109	37	26	752
47.268	55	15	1	.	.	.	1	.	.	6	72	.	1	.	1	.	1	.	6	29	3	.	191
47.272	21	6	5	.	.	.	.	.	.	2	.	.	.	.	.	.	1	11	1	18	12	9	86
47.276	1935	208	6	.	.	2	45	2	.	3	1	.	.	.	1	.	3	5	2	29	.	.	2242
47.278	54	38	.	.	.	.	6	.	.	.	.	.	1	.	.	1	.	1	2	8	.	.	111
47.280	175	8	3	.	.	2	14	.	.	5	.	.	.	.	.	.	.	1	.	1	.	.	209
47.283	184	6	6	.	.	.	4	.	.	2	.	.	.	.	.	.	.	3	.	5	.	2	212
47.286	1272	15	70	.	.	3	18	1	1	3	.	.	.	1	.	1	.	1	.	12	.	5	1403
47.288	1311	44	17	.	13	2	11	.	.	7	1	.	.	.	.	.	.	2	.	5	1	5	1414
47.290	186	11	93	.	2	3	4	.	.	10	2	.	.	.	2	.	1	.	.	2	.	3	319
47.292	276	30	46	.	6	.	7	4	.	9	2	.	.	.	2	.	.	5	.	9	3	3	402
47.295	702	101	103	1	4	6	7	15	.	8	1	1	1	2	1	.	1	4	2	17	4	4	985
47.297	552	136	64	.	4	16	17	11	.	16	3	1	2	5	.	.	4	13	.	26	1	11	882
47.301	438	54	71	.	5	8	6	10	2	15	2	1	.	.	1	.	3	6	.	8	2	.	634
47.304	92	21	27	.	1	1	4	7	.	9	2	.	2	.	.	.	1	2	.	6	2	3	180
47.306	309	68	70	.	5	18	15	10	2	12	1	.	1	1	1	1	3	13	.	18	4	18	570
47.310	780	154	54	.	9	33	18	51	2	8	10	.	.	2	5	3	2	36	.	42	22	18	1249
47.314	241	83	18	.	6	11	24	14	.	2	.	1	1	2	1	5	4	13	.	24	5	1	456
47.318	73	58	17	.	4	10	23	22	.	2	.	.	.	.	.	2	1	17	.	4	.	15	248
47.322	152	33	14	.	.	5	61	3	3	24	.	.	.	.	.	.	1	13	.	14	11	4	338

APPENDIX TABLE 1.—Counts of fish larvae, tabulated by family, for all stations occupied on the second multivessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	Myctophidae	Gonostomatidae	Sternopychidae	Chauliodontidae	Idiacanthidae	Other Stomatoidae	Bathylagidae	Paralepididae	Scopelarchidae	Melamphidae	Bregmacerothidae	Exocoetidae	Trachipteridae	Apogonidae	Bramidae	Chiasmodontidae	Coryphaenidae	Nomeidae	Scombridae	Other identified larvae	Unidentified larvae	Disintegrated larvae	Total fish larvae
47.326	217	43	11	.	.	2	152	15	1	58	.	.	2	.	1	4	.	26	.	50	.	3	582
47.330	436	148	80	.	2	11	137	56	1	14	.	.	.	.	.	12	.	16	.	18	1	15	947
47.334	165	29	32	.	1	9	53	21	.	3	.	.	.	.	.	2	.	4	.	1	.	1	321
47.338	78	19	51	.	.	8	24	8	.	4	.	.	.	.	.	.	.	7	.	.	.	.	199
47.342	302	24	62	3	1	2	19	32	1	8	.	.	.	.	.	4	.	4	.	10	.	.	472
47.345	856	45	78	2	2	11	26	6	.	11	.	.	.	.	.	.	.	15	.	.	.	9	1061
47.349	288	61	47	.	.	5	16	.	1	1	.	.	.	.	.	1	.	2	.	1	.	1	426
47.351	684	66	85	5	1	10	60	3	5	11	.	.	.	.	.	6	.	13	.	2	6	9	966
47.354	71	87	.	.	.	1	.	.	.	.	.	1	.	.	.	.	.	7	.	.	.	1	168
47.357	239	67	27	1	.	4	14	4	5	5	.	.	.	.	1	2	.	15	.	2	2	2	390
47.359	68	56	23	.	.	2	10	1	2	.	.	.	.	.	.	.	.	5	.	.	1	7	176
47.362	81	4	34	11	.	.	3	.	3	1	.	.	.	.	.	.	.	.	.	.	1	1	139
47.364	96	7	4	.	1	.	3	.	.	2	.	.	.	.	.	.	.	3	.	.	.	.	116
47.367	97	24	22	6	1	.	11	.	1	3	.	.	.	.	.	1	.	8	.	3	.	3	180
47.369	13	4	1	.	1	.	3	.	.	1	.	.	.	.	.	.	.	1	.	2	.	.	26
47.371	49	12	1	.	.	1	2	.	.	2	.	.	.	.	.	1	.	.	.	2	.	.	70
47.373	260	239	48	1	3	.	2	3	2	1	1	.	.	.	.	.	.	.	.	16	1	2	579
47.376	52	76	16	3	5	.	9	.	.	5	.	.	.	.	.	.	.	1	.	1	.	5	173
47.379	7	56	9	3	.	.	8	.	.	1	1	.	.	.	2	4	.	.	.	3	1	.	95
47.382	35	114	20	7	3	3	4	.	.	4	.	.	.	.	.	5	.	.	.	1	1	4	205
47.415	30	10	4	.	.	2	.	.	.	.	1	.	.	.	.	.	.	.	.	2	.	.	49
47.430	82	109	7	1	1	.	1	.	.	1	.	1	.	.	.	.	.	.	.	7	.	.	210
47.432	142	101	21	.	3	.	.	2	.	1	2	.	.	.	.	.	.	.	.	2	.	2	276
47.436	10	2	11	.	.	3	2	.	2	1	.	1	.	.	2	.	.	2	.	25	1	2	64
47.438	100	35	14	1	1	3	1	2	.	6	.	.	.	8	1	.	1	11	.	28	2	1	215
47.440	34	109	30	3	.	10	.	1	.	1	.	.	.	1	.	3	.	.	.	12	8	.	212
47.443	56	17	57	.	.	2	1	1	.	3	.	1	.	.	.	.	.	1	.	6	.	1	146
47.446	152	4	2	.	.	1	2	.	.	4	.	.	.	.	.	.	.	.	.	8	.	.	173
47.450	570	85	126	10	.	12	20	41	.	10	.	.	.	.	.	2	.	4	.	41	3	12	936
47.454	200	24	79	1	.	.	6	41	40	.	6	.	.	.	.	3	.	1	.	4	1	5	407
47.458	32	5	6	.	.	3	42	37	.	3	.	.	.	.	.	1	.	1	.	3	.	8	141
47.462	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1
47.466	84	8	3	.	.	3	7	14	.	2	.	.	.	.	.	.	.	.	.	30	.	1	152
47.470	81	110	7	.	.	.	6	4	.	1	.	.	.	.	.	.	.	.	.	5	1	.	215
47.473	38	36	34	.	2	3	6	4	.	1	.	.	.	.	.	3	.	2	.	1	.	.	130
47.486	194	38	29	.	.	1	11	12	.	2	1	.	3	3	1	2	4	7	.	11	1	4	324
47.490	238	24	25	.	1	1	13	20	.	7	.	.	.	2	2	2	1	1	.	7	3	17	364
47.494	77	13	40	.	1	.	2	.	1	7	.	.	.	.	.	.	.	.	.	.	1	2	141
47.498	366	75	111	.	.	7	1	6	2	6	2	.	1	.	.	.	1	.	.	3	5	6	592
47.501	454	165	80	2	2	8	13	.	.	3	.	.	.	.	.	1	3	4	1	7	1	28	772
47.504	628	59	91	1	.	7	20	.	1	4	.	1	.	.	.	.	2	44	.	4	5	28	895
47.507	305	77	33	.	2	6	6	2	.	3	.	9	1	.	.	3	1	3	33	7	1	26	518
47.509	986	65	186	2	2	2	26	.	.	5	.	.	.	.	.	2	.	8	2	10	.	35	1331
47.511	346	2	4	.	2	.	11	.	.	1	.	1	.	.	.	.	.	1	.	3	1	.	372
47.513	80	4	.	.	.	.	.	.	3	.	.	2	1	.	.	.	.	2	.	2	.	.	94
47.515	35	11	14	.	.	.	7	.	.	3	.	.	.	.	.	.	.	2	.	1	1	6	80
47.517	34	36	1	.	.	.	1	.	.	3	.	.	.	.	.	.	.	3	2	4	.	1	85
47.520	55	80	.	.	4	.	3	3	1	6	.	.	.	.	.	.	.	4	.	44	.	1	201
47.523	4	30	.	.	1	.	7	.	1	3	.	.	.	.	.	.	.	3	5	8	.	1	63
47.525	7	10	.	.	.	.	6	.	1	2	3	.	.	.	.	.	1	.	4	13	1	4	52
47.527	550	132	.	.	2	.	3	.	.	3	753	.	.	.	.	.	1	5	25	580	52	12	2118

APPENDIX TABLE 2.—Myctophid larvae, tabulated by genus or species, for all stations occupied on the second multi-vessel EASTROPAC survey (EASTROPAC II).

STATION NUMBER	<u>Diogenichthys laternatus</u>	<u>Lampanyctus</u> spp.	<u>Benthosema panamense</u>	<u>Ceratoscopelus townsendi</u>	<u>Diaphus</u> spp.	<u>Goniichthys tenuiculus</u>	<u>Hygophum atratum</u>	<u>Hygophum proximum</u>	<u>Lampadena</u> spp.	<u>Lepidophanes pyrrobolus</u>	<u>Loweina laurae</u> (rare)	<u>Myctophum auroclaternatum</u>	<u>Myctophum nitidulum</u>	<u>Myctophum</u> spp. (other)	<u>Notolycnus valdiviae</u>	<u>Notoscopelus resplendens</u>	<u>Protomyctophum</u> sp.	<u>Symbolophorus evermanni</u>	<u>Triphoburus</u> spp.	Other identified ¹ myctophids	Unidentified myctophids	Disintegrated myctophids	Total myctophids
45.016	2	5	.	1	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	12
45.018	9	10	.	1	.	1	10	1	.	2	.	.	.	.	.	.	.	.	.	.	.	1	35
45.020	10	.	.	.	.	.	1	.	.	1	.	.	.	.	.	.	1	1	.	.	.	.	14
45.021	7	1	.	.	.	.	4	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	13
45.023	13	6	.	.	5	.	35	1	.	.	.	.	.	.	.	.	.	1	.	.	.	.	61
45.024	20	6	.	.	4	2	52	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	86
45.026	27	1	.	.	3	1	4	1	.	2	.	.	.	.	1	.	.	.	.	.	.	.	40
45.028	22	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	24
45.030	9	1	.	.	10	.	7	3	.	.	.	.	.	.	.	.	.	.	.	.	3	1	34
45.032	109	1	.	.	32	1	5	1	.	.	.	3	.	.	.	.	.	4	.	.	1	1	158
45.034	138	1	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	5	146
45.035	36	1	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	.	40
45.037	36	.	.	.	2	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	1	41
45.039	52	.	.	.	12	1	.	.	.	.	.	.	.	.	.	.	.	8	.	.	.	4	77
45.041	22	1	.	.	4	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	29
45.043	14	.	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	17
45.044	28	1	.	.	19	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	50
45.046	23	1	.	.	16	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	43
45.048	20	.	.	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	25
45.050	16	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	19
45.051	70	6	.	.	.	1	.	.	.	.	.	1	.	.	5	.	.	3	1	.	.	.	87
45.053	36	.	.	.	3	.	.	9	.	.	.	.	.	.	9	.	.	16	.	.	.	2	75
45.054	26	.	.	.	.	.	.	2	.	.	.	.	.	.	2	.	.	9	.	.	.	5	44
45.056	7	1	.	.	.	.	.	2	.	.	.	.	1	.	4	.	.	5	1	.	.	1	22
45.058	51	4	.	.	11	.	14	.	3	.	1	2	20	8	.	.	.	21	.	.	2	9	146
45.060	13	1	.	.	13	.	12	.	1	.	.	.	.	11	.	.	1	25	1	.	.	4	82
45.063	.	.	.	.	2	.	6	1	.	.	.	2	.	.	.	.	.	6	1	.	1	10	29
45.065	.	31	.	.	14	.	16	.	.	.	7	.	8	7	2	.	.	2	2	.	.	27	116
45.067	12	46	.	.	35	1	17	.	1	3	12	.	31	3	3	.	.	4	6	.	4	7	185
45.071	5	14	.	.	3	.	5	.	.	1	2	.	8	1	2	.	.	.	.	.	.	1	42
45.073	11	6	.	.	14	.	6	.	.	.	2	.	12	1	.	.	.	.	.	.	2	11	65
45.078	15	33	.	.	7	.	5	.	.	.	1	.	7	.	.	2	.	.	.	.	.	1	71
45.083	23	4	.	.	.	.	1	2	.	1	.	.	.	.	.	.	.	.	.	.	1	5	37
45.086	15	8	.	.	.	.	2	1	.	.	.	.	9	12	5	2	.	2	1	.	.	8	65
45.090	16	5	.	.	.	.	4	.	.	.	.	1	7	1	.	.	.	2	.	.	1	10	47
45.094	42	28	.	.	1	.	2	15	.	.	.	.	28	.	.	.	.	.	.	.	.	34	150
45.098	15	1	.	.	1	.	1	3	.	.	.	3	12	.	.	.	.	.	.	.	2	5	43
45.102	20	48	.	.	7	4	16	.	.	.	2	.	18	.	.	.	.	.	.	.	.	19	136
45.106	166	10	.	.	2	1	13	.	.	.	2	.	55	1	.	3	.	1	.	.	2	8	265
45.110	298	38	.	.	9	1	9	116	.	.	.	2	51	.	5	.	2	4	2	3	1	4	545
45.114	13	9	.	.	.	.	.	.	.	.	.	.	10	.	1	.	.	.	.	.	.	7	40
45.117	53	6	.	.	1	.	4	.	.	.	.	.	2	.	8	.	.	1	.	.	.	17	92
45.121	25	16	.	.	.	.	1	1	.	1	.	.	.	.	1	.	.	.	1	.	.	9	55
45.125	.	19	.	.	.	.	1	2	.	1	2	1	.	.	6	1	.	2	1	.	1	4	41
45.127	.	9	.	.	.	.	2	.	.	.	1	.	.	.	1	1	.	.	2	.	5	.	21
45.129	.	8	.	.	.	.	3	.	.	1	.	.	.	.	4	.	.	1	1	.	4	.	22
45.131	.	26	.	.	8	1	3	.	.	.	.	.	.	.	14	.	.	7	.	.	1	13	73
45.133	.	21	.	145	35	.	42	.	26	.	.	.	.	3	4	.	.	13	2	.	7	25	323
45.135	.	8	.	77	20	.	30	1	.	.	.	.	.	1	.	2	.	12	1	2	6	5	165
45.137	.	1	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	3	5	11
45.139	.	3	.	2	1	.	1	.	.	.	.	.	.	.	.	.	.	.	.	1	16	.	24
45.140	.	25	.	26	15	.	5	1	.	.	.	.	.	.	2	.	.	27	.	.	.	5	106

APPENDIX TABLE 2.—Myctophid larvae, tabulated by genus or species, for all stations occupied on the second multi-vessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	<u>Diogenichthys laternatus</u>	<u>Lampanyctus</u> spp.	<u>Benthosema panamense</u>	<u>Ceratoscopelus townsendi</u>	<u>Diaphus</u> spp.	<u>Goniichthys tenuiculus</u>	<u>Hygophum atratum</u>	<u>Hygophum proximum</u>	<u>Lampadena</u> spp.	<u>Lepidophanes pyrosobolus</u>	<u>Loweina laurae</u> (rare)	<u>Myctophum aurolaternatum</u>	<u>Myctophum nitidulum</u>	<u>Myctophum</u> spp. (other)	<u>Notolycichthys valdiviae</u>	<u>Notoscopelus resplendens</u>	<u>Protomyctophum</u> sp.	<u>Symbolophorus evermanni</u>	<u>Triphoturus</u> spp.	Other identified ¹ myctophids	Unidentified myctophids	Disintegrated myctophids	Total myctophids
45.163	.	1	.	5	.	.	.	.	1	.	.	.	.	7	.	.	.	6	.	.	1	4	8
45.165	.	23	.	48	20	.	.	36	.	.	.	1	.	.	.	.	.	7	.	.	12	86	152
45.167	.	6	.	43	2	.	.	15	.	.	.	.	.	1	.	.	.	7	.	.	7	56	86
45.169	.	7	.	9	7	.	.	17	.	.	.	.	.	7	1	.	.	1	.	.	3	26	56
45.171	.	5	.	5	5	.	.	.	.	1	.	.	.	1	2	.	.	2	.	.	2	7	26
45.173	.	1	.	.	.	.	.	9	.	.	.	.	.	1	.	.	.	.	.	.	2	.	10
45.175	32	12	.	3	.	.	.	11	.	.	.	.	.	.	.	.	.	2	.	.	2	62	70
45.177	23	43	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	.	.	.	5	59
45.179	39	12	.	.	.	.	.	2	.	.	.	1	.	.	.	.	.	.	.	.	.	7	26
45.183	14	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	255
45.187	244	8	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	2	.	.	5	144
45.191	115	13	.	.	.	.	1	2	.	.	.	1	.	2	.	.	2	.	3	.	10	49	49
45.194	27	3	.	.	.	.	3	.	.	.	.	4	.	2	.	.	2	.	2	.	39	251	53
45.198	116	35	.	1	.	10	3	.	.	.	.	44	.	1	.	1	1	.	.	.	4	22	102
45.202	10	24	.	1	.	.	.	.	.	.	.	16	.	.	.	.	.	.	.	.	1	5	22
45.206	4	10	.	.	.	.	.	.	.	.	.	3	1	.	.	.	.	.	.	.	4	5	102
45.283	26	56	.	.	.	.	.	.	.	.	.	14	.	.	.	.	.	.	.	.	1	1	25
45.287	.	22	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	5	157
45.289	68	74	.	.	.	.	1	.	.	1	1	3	1	.	.	3	.	.	.	.	5	157	157
45.293	127	13	.	.	.	.	1	1	.	5	1	8	12	6	1	3	.	4	.	1	.	5	231
45.297	163	18	.	4	.	.	.	1	.	.	.	1	2	1	.	.	7	.	.	1	2	1	24
45.301	6	5	.	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	119	44
45.305	15	29	.	.	30	.	18	.	.	.	.	2	2	12	2	.	2	3	.	1	1	6	49
45.309	10	6	.	.	.	.	2	1	.	3	.	.	.	2	4	.	.	13	.	1	1	1	44
45.313	33	.	.	.	.	.	3	1	.	.	1	.	1	.	.	.	.	2	.	2	.	6	49
45.316	10	2	.	9	.	.	3	.	.	2	.	5	.	2	.	1	.	.	.	1	4	41	32
45.319	14	.	.	4	.	.	4	.	.	1	2	1	4	2	5	.	.	1	.	1	2	8	45
45.321	19	.	.	2	.	.	.	3	.	.	.	1	.	.	1	.	.	11	.	.	3	51	1002
45.323	32	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	.	.	.	2	69
45.325	967	29	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	1	108
45.329	49	16	.	.	3	.	.	.	.	.	.	.	.	3	.	.	.	.	.	.	.	3	65
45.331	218	13	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	3	49
45.333	84	12	.	9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	235	69
45.335	47	.	.	16	.	2	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	1	108
45.337	37	1	.	4	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	65
45.339	9	.	.	15	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	49
45.341	17	2	.	26	.	2	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1	26	47
45.343	6	.	.	9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	17
45.344	3	1	.	15	.	1	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	21
45.346	6	2	.	10	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	19
45.348	12	5	.	9	.	2	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	2	30
45.350	39	1	.	25	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	70
45.352	17	.	.	4	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	5	29
45.356	40	.	.	24	.	1	.	.	.	.	.	4	.	.	.	.	.	.	.	.	.	.	69
45.358	46	.	.	49	.	.	.	.	.	.	.	3	.	.	.	.	.	.	.	.	.	.	98
45.360	9	1	.	5	.	1	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	18
45.362	1	.	5	26	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	3	36
45.365	.	.	58	39	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	99
45.367	5	.	.	12	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	5	23
45.369	53	2	9	34	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	1	101
45.371	32	1	.	50	.	24	.	.	.	.	.	5	.	.	.	.	.	.	.	2	1	101	120
45.373	59	1	.	36	.	20	.	.	.	.	.	1	.	.	.	.	.	.	.	1	3	117	117

APPENDIX TABLE 2.—Myctophid larvae, tabulated by genus or species, for all stations occupied on the second multi-vessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	<u>Diogenichthys laternatus</u>	<u>Lampanyctus</u> spp.	<u>Benthosema panamense</u>	<u>Ceratoscopelus townsendi</u>	<u>Diaphus</u> spp.	<u>Goniichthys tenuiculus</u>	<u>Hygophum atratum</u>	<u>Hygophum proximum</u>	<u>Lampadena</u> spp.	<u>Lepidophanes pyrosobolus</u>	<u>Loweina laurae</u> (rara)	<u>Myctophum aulaternatum</u>	<u>Myctophum nitidulum</u>	<u>Myctophum</u> spp. (other)	<u>Notolichnus valdiviae</u>	<u>Notoscopelus resplendens</u>	<u>Protomyctophum</u> sp.	<u>Symbolophorus evermanni</u>	<u>Triphoturus</u> spp.	Other identified ¹ myctophids	Unidentified myctophids	Disintegrated myctophids	Total myctophids
45.375	20	.	.	.	8	.	2	.	.	.	.	1	.	.	.	.	.	.	.	.	1	2	34
45.377	42	.	.	.	22	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	67
45.379	42	8	.	.	63	.	85	.	.	.	.	1	.	.	.	.	.	.	.	.	1	.	199
45.381	59	.	.	.	13	.	19	.	.	.	.	5	.	.	.	.	.	.	.	.	.	2	98
45.383	37	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	40
45.385	7	.	.	.	1	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	19
45.387	6	12	.	.	2	.	2	.	.	.	.	.	.	.	.	.	.	.	1	.	1	2	26
CRUISE 46																							
46.002	.	.	.	.	12	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	14
46.004	7	1	.	.	94	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	103
46.006	2	.	.	.	27	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	30
46.007	1	.	.	.	9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	10
46.009	.	1	.	.	16	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	17
46.011	26	.	.	.	33	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	60
46.013	31	2	.	.	55	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	89
46.015	1	.	.	.	17	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	18
46.017	1	.	.	.	23	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	25
46.019	114	4	.	.	163	.	.	.	.	.	.	3	.	.	.	.	.	.	.	.	.	1	285
46.020	75	3	.	.	76	.	.	.	.	.	.	2	.	.	.	.	.	3	.	.	.	1	160
46.022	38	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	38
46.024	60	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	64
46.026	150	53	.	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	206
46.028	343	32	.	.	30	3	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	3	412
46.030	80	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	1	.	.	.	3	85
46.032	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	1	1	9
46.034	117	8	.	.	6	1	.	.	.	.	.	.	2	.	11	.	.	5	.	1	1	1	152
46.036	357	20	.	.	.	.	.	.	.	.	.	3	2	.	36	.	.	14	1	.	.	3	436
46.038	12	1	.	.	.	.	.	.	.	.	.	.	1	.	3	.	.	1	.	.	1	1	20
46.040	19	2	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	.	.	2	.	25
46.042	31	1	.	.	2	.	.	3	2	8	.	4	.	1	2	.	1	4	2	.	1	.	62
46.044	69	3	.	.	6	.	.	.	.	.	.	.	.	.	3	.	.	4	.	.	.	4	89
46.046	51	1	.	.	16	.	.	.	3	1	.	2	.	1	.	.	.	.	.	.	.	3	78
46.048	50	1	.	.	5	.	1	.	.	1	.	.	3	.	.	.	1	1	.	.	.	.	63
46.050	163	13	.	.	8	.	14	1	2	.	.	4	4	12	8	.	1	9	2	1	.	8	250
46.052	207	21	.	.	5	.	2	9	10	1	3	2	23	13	2	1	9	.	.	11	.	.	319
46.054	126	23	.	.	.	.	1	.	.	.	.	3	5	11	16	1	.	15	.	.	.	10	211
46.055	65	15	.	.	.	2	1	.	.	.	.	2	.	4	1	6	.	1	.	.	.	3	100
46.057	366	241	.	.	4	11	3	17	17	2	8	31	.	5	13	.	8	22	.	3	.	.	751
46.059	133	250	.	.	.	9	11	.	8	.	5	10	3	6	16	.	3	17	.	3	20	494	
46.061	71	36	.	.	.	1	.	.	.	.	.	.	11	.	1	2	.	.	1	.	.	25	148
46.063	14	27	.	.	.	.	.	.	.	.	.	.	4	.	.	.	.	.	.	.	.	3	48
46.065	189	84	.	.	7	5	18	14	.	1	.	56	.	.	.	24	.	1	3	.	.	2	404
46.067	164	73	.	.	3	.	7	4	.	.	.	.	7	.	.	3	1	.	1	.	3	3	269
46.069	46	64	.	.	2	.	.	1	.	.	.	1	2	.	.	.	.	.	.	.	.	.	116
46.071	21	34	.	.	2	.	.	.	.	2	.	1	.	.	.	1	.	.	.	.	1	10	72
46.075	19	14	.	.	.	.	.	.	.	.	.	1	.	.	.	1	.	.	.	.	.	.	35
46.077	30	6	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	36
46.079	285	28	.	.	4	21	.	.	.	.	2	18	.	.	.	33	.	1	13	.	1	2	408
46.082	35	2	.	.	1	6	.	.	.	.	.	1	4	.	.	5	.	.	.	.	5	2	61

APPENDIX TABLE 2.—Myctophid larvae, tabulated by genus or species, for all stations occupied on the second multi-vessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	<u>Diogenichthys laternatus</u>	<u>Lampanyctus</u> spp.	<u>Bentoseia panamense</u>	<u>Ceratoscopelus townsendi</u>	<u>Diaphus</u> spp.	<u>Goniichthys tenuiculus</u>	<u>Hygophum atratum</u>	<u>Hygophum proximum</u>	<u>Lampadena</u> spp.	<u>Lepidophanes pyrosobolus</u>	<u>Lowena laurae</u> (rare)	<u>Myctophum auroalternatum</u>	<u>Myctophum nitidulum</u>	<u>Myctophum</u> spp. (other)	<u>Notolynchus valdiviae</u>	<u>Notoscopelus resplendens</u>	<u>Protomyctophum</u> sp.	<u>Symbolophorus evermanni</u>	<u>Triphoturus</u> spp.	Other identified ¹ myctophids	Unidentified myctophids	Disintegrated myctophids	Total myctophids
46.084	23	9	.	.	.	.	.	.	.	.	.	1	3	.	.	5	.	.	.	.	4	.	45
46.086	68	20	.	.	.	3	.	.	.	1	.	2	2	.	.	4	.	.	1	.	1	.	102
46.088	69	23	.	.	.	2	.	.	.	.	.	6	3	.	.	16	.	2	.	.	3	.	124
46.090	72	10	.	.	5	1	.	.	.	.	1	.	2	.	.	1	.	.	.	.	7	.	99
46.092	88	4	.	.	1	.	.	.	.	1	.	.	1	.	.	2	.	.	2	.	1	.	100
46.094	196	25	.	.	8	1	.	.	.	3	.	5	13	3	25	3	1	1	9	1	4	2	300
46.096	144	37	.	.	9	.	.	4	.	8	.	8	4	7	6	1	3	8	1	1	.	240	
46.098	50	.	.	.	1	.	.	3	.	.	.	1	3	5	3	1	3	1	.	.	2	73	
46.100	105	.	.	.	3	.	.	.	.	.	.	.	5	5	4	6	.	.	2	.	.	125	
46.102	273	27	.	.	.	3	.	1	.	.	.	3	1	.	10	.	5	7	.	.	1	334	
46.104	70	15	.	.	.	.	.	.	.	.	.	2	2	.	15	.	.	1	.	1	3	109	
46.106	110	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	115	
46.108	241	8	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	250	
46.110	151	10	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	162	
46.112	530	13	.	.	16	.	.	.	.	.	.	.	.	.	1	.	2	.	.	1	.	562	
46.114	12	.	.	.	16	.	.	.	.	.	.	3	.	.	.	.	.	.	.	.	.	31	
46.116	9	.	.	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	14	
46.118	50	6	.	.	111	1	1	.	.	1	.	7	.	.	.	.	.	.	.	.	.	176	
46.120	19	.	.	.	56	.	.	.	.	.	.	5	.	.	.	.	.	.	.	.	.	80	
46.122	.	.	.	.	11	.	.	.	.	.	.	1	.	.	.	.	.	.	.	3	2	17	
46.124	.	.	.	.	19	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	19	
46.126	11	4	.	.	46	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	63	
46.128	1	1	.	.	97	.	.	.	.	.	.	6	.	.	.	.	.	.	.	.	.	113	
46.130	9	.	.	.	37	.	.	.	.	.	.	.	.	.	.	.	.	.	.	6	2	46	
46.132	3	1	.	.	22	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	26	
46.134	2	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	9	
46.135	.	.	81	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	81	
46.137	201	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	201	
46.139	160	14	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	175	
46.141	435	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	438	
46.143	112	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	113	
46.145	269	10	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	282	
46.147	480	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	484	
46.149	1328	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1333	
46.151	1358	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1358	
46.153	2505	49	.	.	.	3	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	3	2561
46.155	939	20	.	.	1	5	.	.	.	.	.	3	.	.	1	.	.	4	.	.	.	973	
46.157	474	3	.	.	.	2	.	.	.	.	.	3	1	.	4	.	.	.	.	.	.	490	
46.159	59	1	.	.	4	2	.	.	.	.	.	3	1	.	4	.	1	.	.	1	1	71	
46.161	268	17	.	.	.	3	.	1	.	.	.	2	2	.	39	2	.	3	6	1	3	350	
46.163	214	28	.	.	1	4	.	1	.	3	2	3	2	.	.	.	.	.	.	.	.	5	290
46.165	48	7	.	.	.	.	.	1	.	11	1	5	4	.	6	1	.	4	.	.	1	90	
46.167	131	25	.	.	.	.	.	.	.	.	.	23	5	.	3	3	.	2	.	.	1	2	195
46.169	89	34	.	.	2	2	.	.	.	.	1	.	3	.	3	13	1	6	1	4	4	163	
46.171	182	8	.	.	1	1	.	.	.	.	.	.	30	.	.	14	.	3	5	.	11	255	
46.173	27	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	33	
46.175	44	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	52	
46.177	105	8	.	.	1	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	124	
46.179	182	14	.	.	1	.	.	.	.	.	.	.	1	.	.	4	.	.	5	.	.	213	
46.181	20	5	.	.	1	1	.	.	.	.	.	.	1	.	.	6	1	1	3	.	.	4	52
46.183	50	9	.	.	4	1	1	.	.	.	.	.	5	.	.	.	.	1	2	.	17	.	85
46.185	178	36	.	.	8	2	.	.	.	.	.	2	8	.	.	11	.	4	11	.	1	1	262

APPENDIX TABLE 2.—Myctophid larvae, tabulated by genus or species, for all stations occupied on the second multi-vessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	<u>Diogenichthys laternatus</u>	<u>Lampanyctus</u> spp.	<u>Benthosema panamense</u>	<u>Ceratoscopelus townsendi</u>	<u>Diaphus</u> spp.	<u>Goniichthys tenuiculus</u>	<u>Hygophum atratum</u>	<u>Hygophum proximum</u>	<u>Lampadena</u> spp.	<u>Lepidophanes pyrsobolus</u>	<u>Loweina laurae</u> (rare)	<u>Myctophum aurolaternatum</u>	<u>Myctophum nitidulum</u>	<u>Myctophum</u> spp. (other)	<u>Notolychnus valdiviae</u>	<u>Notoscopelus resplendens</u>	<u>Protomyctophum</u> sp.	<u>Symbolophorus evermanni</u>	<u>Triphoturus</u> spp.	Other identified ¹ myctophids	Unidentified myctophids	Disintegrated myctophids	Total myctophids
46.187	468	40	.	.	.	.	.	.	.	.	.	2	1	.	.	.	.	2	2	.	.	1	516
46.189	234	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	236
CRUISE	47																						
47.001	68	13	.	.	8	2	.	.	.	.	.	2	1	.	.	1	.	1	1	.	.	.	97
47.005	161	33	9	.	33	1	.	.	.	.	.	19	6	.	.	.	.	17	1	.	.	7	287
47.008	205	31	5	.	4	2	.	.	.	.	.	4	.	.	.	.	.	3	1	.	.	2	257
47.011	117	22	13	.	2	.	.	.	.	.	.	3	.	.	.	.	.	3	1	.	.	.	161
47.019	287	37	2	.	39	.	.	.	.	.	.	1	.	.	.	.	.	2	2	.	.	.	370
47.022	148	11	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	1	2	.	5	.	169
47.025	73	5	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	2	83
47.028	175	66	.	.	5	1	.	.	.	.	.	7	.	.	.	.	.	9	.	.	1	.	264
47.032	148	38	.	.	12	.	.	.	.	.	.	3	.	.	.	.	.	6	1	.	.	.	208
47.034	95	23	.	.	.	1	.	.	.	.	.	7	4	.	.	.	.	6	.	.	.	3	139
47.035	171	21	.	.	1	3	.	.	.	.	.	9	12	.	.	.	.	3	1	.	1	.	223
47.040	129	38	11	.	3	.	.	.	.	.	.	10	6	.	.	.	.	.	.	6	2	.	205
47.049	42	9	.	.	1	.	.	.	.	.	.	4	3	.	.	.	.	1	2	.	1	.	64
47.053	105	89	.	.	1	4	.	.	.	.	.	19	18	.	.	11	.	2	3	.	9	4	265
47.057	192	50	.	.	.	1	.	.	.	.	.	23	1	.	.	6	.	1	12	.	11	3	300
47.061	22	12	.	.	3	2	.	.	.	.	.	4	23	.	.	1	.	.	9	.	.	3	79
47.065	31	22	.	.	1	3	.	.	.	.	.	2	12	.	.	.	.	22	.	.	6	.	99
47.069	29	6	.	.	2	3	.	.	.	.	.	35	.	.	.	28	.	2	5	.	30	.	140
47.070	50	11	.	.	.	.	.	.	.	.	.	1	17	.	.	.	.	1	10	.	.	.	90
47.074	98	4	.	.	1	1	.	.	.	.	.	.	26	.	.	1	.	.	5	.	2	.	138
47.078	5	.	.	.	1	.	.	.	.	.	.	.	3	.	.	.	.	.	2	.	.	.	11
47.082	70	10	.	.	.	.	.	.	.	.	.	.	11	.	.	.	.	.	6	.	15	7	119
47.086	212	10	.	.	.	.	.	.	.	.	.	.	6	.	.	.	.	18	.	1	.	1	248
47.090	33	17	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	2	.	.	3	57
47.094	96	.	.	.	.	.	.	.	.	.	.	.	3	.	.	.	.	.	.	.	.	1	100
47.097	9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	6	16
47.099	6	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	16
47.101	39	6	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	2	48
47.103	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	2
47.105	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4
47.107	30	70	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	6	.	.	1	109
47.109	1	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	6
47.113	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
47.124	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	.	.	.	.	10
47.128	.	31	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	.	.	.	.	35
47.132	15	53	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	12	.	.	3	85
47.134	5	10	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	1	1	.	1	1	21
47.137	4	4	.	.	.	.	.	.	.	.	.	.	.	.	1	1	.	2	3	1	1	1	17
47.139	3	7	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	3	1	.	.	.	16
47.141	12	5	.	.	.	2	1	.	.	.	.	.	.	.	.	.	.	1	1	.	1	1	24
47.143	19	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	23
47.145	.	2	.	.	.	6	.	.	.	.	.	1	.	.	.	2	.	1	1	.	2	.	15
47.147	2	2	.	.	.	16	.	.	.	.	1	4	.	.	.	1	.	3	8	5	1	1	44
47.149	12	7	.	.	.	10	.	.	.	.	.	.	1	.	.	.	.	.	6	.	3	1	40
47.151	6	1	.	.	.	5	3	.	.	.	.	1	.	.	.	.	.	1	4	.	.	1	22
47.153	6	3	.	.	.	1	11	.	.	.	.	1	.	.	.	.	.	1	3	.	3	1	30

APPENDIX TABLE 2.—Myctophid larvae, tabulated by genus or species, for all stations occupied on the second multi-vessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	<u>Diogenichthys laternatus</u>	<u>Lampanyctus</u> spp.	<u>Benthosema panamense</u>	<u>Ceratoscopelus townsendi</u>	<u>Diaphus</u> spp.	<u>Goniichthys tenuiculus</u>	<u>Hygophum atratum</u>	<u>Hygophum proximum</u>	<u>Lampadena</u> spp.	<u>Lepidophanes pyrosobolus</u>	<u>Loweina laurae</u> (rare)	<u>Myctophum aurolaternatum</u>	<u>Myctophum nitidulum</u>	<u>Myctophum</u> spp. (other)	<u>Notolychnus valdiviae</u>	<u>Notoscopelus resplendens</u>	<u>Protomyctophum</u> sp.	<u>Symbolophorus evermanni</u>	<u>Triphoturus</u> spp.	Other identified ¹ myctophids	Unidentified myctophids	Disintegrated myctophids	Total myctophids
47.155	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
47.157	72	8	.	.	.	.	16	.	.	.	.	.	1	.	1	.	.	2	6	.	.	.	109
47.159	9	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	.	2	1	17
47.162	.	2	.	.	.	.	5	.	.	.	.	.	.	.	.	.	.	.	4	.	.	.	11
47.164	9	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	5	5	.	4	.	25
47.166	11	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	7	.	6	.	28
47.168	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	1	6	
47.171	50	12	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	3	.	.	.	66
47.173	179	35	.	.	.	.	.	.	.	.	.	2	4	.	.	.	.	30	.	1	.	.	251
47.175	265	15	.	.	.	.	.	.	.	.	.	.	9	.	.	.	.	1	37	.	.	.	327
47.177	60	13	.	.	.	.	.	.	.	.	.	1	13	.	.	.	.	1	27	.	.	4	119
47.179	190	4	.	.	.	1	.	.	.	.	.	.	4	.	.	.	.	21	.	.	8	228	
47.181	126	6	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	1	12	.	1	2	150
47.185	281	16	.	.	.	2	.	.	.	.	.	.	13	.	.	3	.	1	34	.	.	.	350
47.189	20	.	.	.	.	2	.	.	.	.	.	.	2	.	.	.	.	4	.	.	.	.	28
47.193	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2
47.197	56	.	.	.	.	2	.	.	.	.	.	.	28	.	.	.	.	.	10	.	.	1	97
47.201	148	75	.	.	11	1	.	.	.	.	.	.	89	.	.	4	.	8	38	.	2	16	392
47.205	51	28	.	.	1	1	.	.	.	.	.	.	19	.	.	.	.	.	3	.	.	6	109
47.213	595	121	.	.	5	2	.	.	.	.	.	14	6	.	.	4	1	9	.	.	12	769	
47.217	360	36	.	.	3	3	.	.	.	.	.	19	4	.	.	5	.	.	6	.	1	3	440
47.221	425	6	.	.	.	.	.	.	.	.	.	5	6	.	2	.	.	.	3	.	.	5	452
47.225	416	54	.	.	2	5	.	.	.	2	.	15	8	.	1	.	.	3	6	.	.	.	512
47.229	265	145	.	.	3	6	.	.	.	.	.	30	10	.	4	.	.	20	4	.	6	3	496
47.233	1206	146	.	.	12	6	.	.	.	.	.	23	.	.	3	1	.	33	2	.	2	7	1441
47.237	86	5	.	.	2	2	.	.	.	.	.	5	.	.	.	.	.	.	.	.	.	.	100
47.240	182	8	.	.	4	2	.	.	.	.	.	4	.	.	1	.	.	.	.	.	.	.	201
47.242	931	16	.	.	4	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	953
47.244	837	58	.	.	2	2	.	.	.	.	.	3	.	.	.	.	.	2	.	.	.	.	905
47.246	103	6	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	111
47.250	295	1	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	297
47.254	224	3	.	.	17	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	245
47.258	11	19	402	.	67	1	.	.	.	.	.	.	.	.	.	.	.	1	.	.	12	3	516
47.268	55	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	55
47.272	21	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	21
47.276	1904	17	.	.	13	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1935
47.278	45	8	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	54
47.280	170	3	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	175
47.283	177	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	184
47.286	1260	10	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1272
47.288	1297	10	.	.	.	1	1	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1	1311
47.290	172	6	.	.	.	.	.	.	.	.	.	1	4	.	.	.	.	2	.	.	.	.	186
47.292	266	4	.	.	.	.	.	.	.	.	.	3	.	.	1	.	.	.	1	.	.	1	276
47.295	627	28	.	.	.	2	.	.	.	.	.	8	1	.	13	.	16	.	1	2	4	702	
47.297	432	51	.	.	.	2	.	.	.	.	.	12	4	.	17	.	27	2	.	.	5	552	
47.301	382	25	.	.	.	8	.	.	.	.	.	7	.	.	6	.	10	.	.	.	.	438	
47.304	56	16	.	.	.	.	.	.	.	.	.	4	2	.	4	.	1	7	1	.	.	1	92
47.306	241	16	.	.	.	3	.	.	.	.	.	19	5	.	11	.	13	.	.	.	1	309	
47.310	552	116	.	.	.	5	.	.	.	1	.	44	3	.	11	.	19	4	.	16	9	780	
47.314	145	62	.	.	.	.	.	.	.	1	.	18	2	.	1	4	.	3	.	5	.	241	
47.318	49	8	.	.	.	.	.	.	.	.	.	4	6	.	.	.	2	1	.	.	3	73	
47.322	111	11	.	.	2	1	.	.	.	.	.	2	19	.	.	2	.	.	3	.	1	.	152

APPENDIX TABLE 2.—Myctophid larvae, tabulated by genus or species, for all stations occupied on the second multi-vessel EASTROPAC survey (EASTROPAC II).—Continued.

STATION NUMBER	<u>Diogenichthys laternatus</u>	<u>Lampanyctus</u> spp.	<u>Bentosema panamense</u>	<u>Ceratoscopelus townsendi</u>	<u>Diaphus</u> spp.	<u>Goniichthys tenuiculus</u>	<u>Hygophum atratum</u>	<u>Hygophum proximum</u>	<u>Lampadena</u> spp.	<u>Lepidophanes pyrrobolus</u>	<u>Lowena laurae</u> (rare)	<u>Myctophum aurolateratum</u>	<u>Myctophum nitidulum</u>	<u>Myctophum</u> spp. (other)	<u>Notolychnus valdiviae</u>	<u>Notoscopelus resplendens</u>	<u>Protomyctophum</u> sp.	<u>Symbolophorus evermanni</u>	<u>Triphoturus</u> spp.	Other Identified myctophids	Unidentified myctophids	Disintegrated myctophids	Total myctophids
47.326	60	42	.	.	16	3	3	.	.	.	1	2	52	.	.	5	.	.	20	.	11	2	217
47.330	193	53	.	.	13	20	.	.	.	.	.	72	72	.	.	30	.	2	51	.	2	.	436
47.334	92	10	.	.	6	2	.	.	.	.	.	1	19	.	.	13	.	4	16	.	1	1	165
47.338	42	15	.	.	.	1	.	.	.	.	.	1	2	.	.	.	.	.	16	.	.	1	78
47.342	227	8	.	.	.	2	.	.	.	.	.	2	57	.	.	1	.	.	5	.	.	.	302
47.345	813	15	.	.	.	1	.	.	.	.	.	1	12	.	.	2	.	1	8	.	.	3	856
47.349	271	2	.	.	1	2	.	.	.	.	.	2	5	.	.	.	.	2	3	.	.	.	288
47.351	662	7	.	.	1	5	.	.	.	.	.	.	5	.	.	.	.	4	.	.	.	.	684
47.354	1	66	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	1	.	.	2	71
47.357	179	21	.	.	.	8	.	.	.	.	.	12	1	.	.	.	.	14	3	.	.	1	239
47.359	60	3	.	.	1	2	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	68
47.362	69	2	.	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	3	.	1	2	81
47.364	76	7	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1	7	.	2	2	96
47.367	71	12	.	.	.	.	1	.	.	.	.	.	.	.	1	.	.	.	7	.	4	1	97
47.369	11	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1	.	.	.	13
47.371	31	4	.	.	.	.	4	.	.	.	.	.	.	.	1	1	.	.	5	3	.	.	49
47.373	155	15	.	.	3	.	44	23	.	.	.	1	.	1	2	.	.	7	2	1	.	6	260
47.376	32	3	.	.	.	.	3	.	.	.	.	1	1	.	4	.	.	3	4	.	.	1	52
47.379	3	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	1	7
47.382	5	2	.	.	.	.	4	.	.	.	.	.	4	.	5	.	.	6	1	.	7	1	35
47.415	6	4	.	.	5	.	.	1	.	.	.	.	.	.	2	1	.	7	.	.	4	.	30
47.430	3	23	.	.	.	.	1	6	.	.	.	.	.	.	4	2	.	35	.	.	8	.	82
47.432	.	34	.	24	12	.	7	14	.	2	.	.	.	.	1	1	1	29	.	5	10	2	142
47.436	5	1	.	.	.	1	.	.	.	.	.	.	.	.	1	.	.	1	.	.	.	1	10
47.438	31	49	.	.	.	1	.	.	.	.	.	4	.	.	.	.	.	14	.	.	.	1	100
47.440	10	9	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	10	.	.	2	1	34
47.443	54	1	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	56
47.446	139	1	.	.	.	4	.	.	.	.	.	4	.	.	.	.	.	2	2	.	.	.	152
47.450	500	19	.	.	.	6	.	.	.	.	.	5	3	.	.	1	.	17	11	.	2	6	570
47.454	153	25	.	.	1	2	.	.	.	.	.	2	1	.	2	.	4	9	.	.	.	1	200
47.458	10	7	.	.	3	1	.	.	.	.	.	1	.	.	3	.	.	5	.	.	.	2	32
47.462	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
47.466	60	5	.	.	2	1	.	.	.	.	.	.	4	.	1	6	.	1	4	.	.	.	84
47.470	39	16	.	.	3	.	.	.	.	.	.	.	14	.	2	.	.	6	.	1	.	.	81
47.478	19	10	.	.	.	.	1	.	.	.	.	4	.	.	1	1	.	1	.	1	.	.	38
47.486	150	12	.	.	.	1	.	1	.	1	2	1	1	.	9	2	.	2	3	.	.	9	194
47.490	199	.	.	.	.	2	.	.	.	2	.	5	2	.	5	5	.	6	.	.	12	238	
47.494	63	4	.	.	.	.	.	.	.	.	.	1	.	.	3	.	1	.	1	.	.	4	77
47.498	296	16	.	.	1	2	.	.	.	2	.	2	4	.	13	1	8	12	2	.	.	7	366
47.501	401	33	.	.	.	3	.	.	.	.	.	5	2	.	.	.	1	3	.	.	.	6	454
47.504	568	15	.	.	1	.	1	.	.	.	3	6	.	.	9	.	1	3	.	.	21	628	
47.507	272	23	.	.	.	4	.	.	.	.	.	3	.	.	.	.	.	.	.	.	.	3	305
47.509	955	24	.	.	.	3	.	.	.	.	.	.	1	.	.	.	1	.	.	.	.	2	986
47.511	344	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	346
47.513	80	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	80
47.515	34	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	35
47.517	32	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	34
47.520	26	9	.	.	18	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	55
47.523	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4
47.525	1	1	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7
47.527	.	.	524	.	24	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	550

APPENDIX TABLE 3.—Counts of selected categories of fish larvae, tabulated by station, EASTROPAC II.

STATION NUMBER	<u>Vinciguerra</u> spp.	<u>Cyclothone</u> spp.	<u>Bathylagus nigrigenys</u>	<u>Leuroglossus stibius urotraneus</u>	<u>Nansenia</u> sp.	<u>Diplophos taenia</u>	<u>Ichthyococcus irregularis</u>	<u>Maurolicus muelleri</u>	<u>Astronesthidae</u>	<u>Bathophilus filifer</u>	<u>Stomias</u> sp.	<u>Evermannellidae</u>	<u>Macroparalepis macrurus</u>	<u>Scopelosauridae</u>	<u>Scomberesocidae</u>	<u>Gempylus serpens</u>	<u>Nealotus tripes</u>	<u>Diplospinus multistriatus</u>	<u>Trichurus lepturus</u>	<u>Tetraodon</u> spp.	<u>Trachichthyidae</u>	<u>Ballistidae</u>	<u>Ostraciontidae</u>	Total; selected categories
45.016	12	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	14
45.018	77	2	.	.	.	2	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	87
45.020	5	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	7
45.021	15	1	.	.	.	1	.	.	.	1	.	.	1	.	.	.	2	.	.	.	.	.	.	25
45.023	101	5	.	.	.	.	.	.	.	2	1	1	.	.	.	.	.	.	.	.	.	.	.	110
45.024	95	1	.	.	.	.	.	.	.	.	1	.	.	.	.	.	2	.	1	.	.	.	.	100
45.026	27	.	4	.	.	3	.	.	.	.	.	.	1	.	.	.	1	.	.	.	.	1	.	38
45.028	21	.	9	.	.	1	.	.	.	3	1	.	.	.	.	.	1	.	.	.	.	.	.	36
45.030	54	1	.	.	.	5	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	61
45.032	178	.	7	.	.	3	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	10	.	129
45.034	35	.	1	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	39
45.035	27	.	2	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	34
45.037	24	.	10	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	35
45.039	77	3	1	.	.	2	.	.	.	2	.	.	1	.	.	.	1	3	.	.	.	.	.	90
45.041	49	.	8	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	58
45.043	16	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	23
45.044	38	1	4	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	45
45.046	56	.	2	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	59
45.048	21	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	23
45.050	2	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4
45.051	8	5	4	.	.	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	19
45.053	7	12	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	.	.	.	.	.	.	22
45.054	2	.	1	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4
45.056	4	2	.	.	.	.	.	.	.	.	.	.	1	.	.	.	2	.	.	.	.	.	.	8
45.058	11	4	1	.	.	3	.	.	.	.	.	3	1	.	.	.	1	.	.	.	.	.	.	24
45.060	1	2	1	.	.	.	.	.	3	2	.	.	.	.	.	.	2	.	.	.	.	.	.	12
45.063	43	2	1	.	.	1	.	.	.	7	.	2	1	.	.	.	1	.	.	.	.	.	.	58
45.065	368	1	.	.	.	1	.	.	.	12	4	4	3	.	.	.	.	.	.	.	.	.	.	397
45.067	560	23	3	.	.	1	.	.	1	39	6	24	28	.	.	.	.	.	.	.	.	.	.	685
45.071	39	1	.	.	.	.	.	.	.	1	1	4	1	.	.	.	.	.	.	.	.	.	.	47
45.073	65	3	2	.	.	.	.	.	.	.	.	1	.	.	.	.	1	.	.	.	.	.	.	73
45.078	105	1	1	.	.	1	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	110
45.083	26	.	.	.	1	.	.	.	.	.	.	1	2	.	.	.	.	.	.	.	.	.	.	30
45.086	77	.	3	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	81
45.090	65	2	8	.	.	.	.	.	.	3	.	5	.	.	.	.	.	.	1	.	.	.	.	84
45.094	100	7	6	.	.	.	.	.	1	.	1	.	1	.	.	.	.	.	.	.	.	.	.	116
45.098	15	.	2	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	18
45.102	78	4	1	.	.	.	.	.	.	2	.	.	.	.	.	.	1	.	.	.	.	.	.	86
45.106	21	.	5	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	28
45.110	27	5	12	.	2	.	.	.	.	.	.	.	1	.	.	.	.	.	.	1	.	.	.	47
45.114	15	5	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	22
45.117	43	5	1	.	.	.	1	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	52
45.121	91	7	4	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	104
45.125	391	74	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	.	.	.	327
45.127	38	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	.	.	.	41
45.129	2	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3
45.131	325	12	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	.	.	.	339
45.133	3	25	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	1	.	.	.	.	.	36
45.135	6	10	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	18
45.137	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
45.139	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2
45.140	12	32	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	52

APPENDIX TABLE 3.—Counts of selected categories of fish larvae, tabulated by station, EASTROPAC II.—*Continued.*

STATION NUMBER	<u>Vinciguerra</u> spp.	<u>Cyclothone</u> spp.	<u>Bathylagus</u> <u>nigrigenys</u>	<u>Leuroglossus</u> <u>stilbus</u> <u>urotrampus</u>	<u>Nansenia</u> sp.	<u>Diplophos</u> <u>taenia</u>	<u>Ichthyococcus</u> <u>irregularis</u>	<u>Maurolicus</u> <u>muelleri</u>	<u>Astronesthidae</u>	<u>Bathophilus</u> <u>filifer</u>	<u>Stomias</u> sp.	<u>Evermannellidae</u>	<u>Macroparalepis</u> <u>macrurus</u>	<u>Scopelosauridae</u>	<u>Scomberesocidae</u>	<u>Gempylus</u> <u>serpens</u>	<u>Nealotus</u> <u>tripes</u>	<u>Diplospinus</u> <u>multistriatus</u>	<u>Trichiurus</u> <u>lephurus</u>	<u>Tetragonurus</u> spp.	<u>Trachichthyidae</u>	<u>Balistidae</u>	<u>Ostracodontidae</u>	Total: selected categories
45.163	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
45.165	33	29	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	66
45.167	3	3	.	.	.	2	.	.	.	1	1	.	.	.	.	.	.	.	.	.	.	.	.	6
45.169	5	15	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	15
45.171	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
45.173	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
45.175	20	7	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	28
45.177	141	7	.	.	1	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	151
45.179	32	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	33
45.183	13	1	4	.	.	.	.	.	.	.	.	.	1	.	.	1	.	.	.	.	.	.	.	20
45.187	15	1	16	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	33
45.191	10	.	5	.	1	.	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	20
45.194	4	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7
45.198	16	5	7	.	2	.	.	.	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	32
45.202	15	4	2	.	2	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	24
45.206	1	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2
45.283	8	.	2	.	2	.	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	17
45.287	79	3	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	84
45.289	114	10	2	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	127
45.293	55	2	4	.	.	.	.	1	.	4	.	.	.	.	.	.	1	.	.	.	.	.	.	67
45.297	103	3	7	.	.	1	.	.	.	15	.	.	.	.	.	.	.	.	.	.	.	.	.	129
45.301	24	1	6	.	1	1	.	.	.	3	3	.	.	.	.	.	.	.	.	.	.	.	.	41
45.305	1035	5	2	.	1	.	.	.	2	1	.	.	.	.	.	.	.	.	.	.	.	.	.	1046
45.309	148	1	.	.	1	1	.	.	3	4	.	.	.	.	.	.	.	.	.	.	.	.	.	158
45.313	34	.	2	.	.	1	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	38
45.316	31	3	1	.	.	.	.	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	38
45.319	45	1	.	.	.	.	.	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	48
45.321	9	5	2	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	15
45.323	2	2	1	.	.	.	.	.	2	1	.	.	.	.	.	1	.	.	.	.	.	.	.	9
45.325	17	11	42	.	.	.	.	.	.	.	.	.	.	.	.	1	1	.	.	.	.	.	.	72
45.329	2	3	3	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	8
45.331	2	3	13	.	.	.	.	.	.	1	.	.	.	.	.	1	.	.	.	.	.	.	.	20
45.333	27	1	5	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	13	47
45.335	27	2	3	.	.	3	.	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	8	51
45.337	12	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	14
45.339	5	.	2	.	.	3	.	.	.	.	.	.	.	.	.	3	.	.	.	.	.	.	5	18
45.341	64	.	3	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	74
45.343	32	.	2	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1	36
45.344	34	.	1	.	.	3	.	.	.	2	.	1	.	.	.	2	.	.	.	.	.	.	2	45
45.346	19	.	.	.	.	.	.	.	.	1	.	.	.	.	.	1	.	.	.	.	.	.	.	21
45.348	120	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	1	123
45.350	296	.	.	.	.	1	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	298
45.352	65	.	3	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	69
45.356	147	.	11	.	.	6	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	165
45.358	102	.	1	.	.	5	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	109
45.360	32	.	7	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	45
45.362	28	.	6	.	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	37
45.365	35	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	56
45.367	10	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	17
45.369	103	.	3	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	108
45.371	230	.	13	.	.	9	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	253
45.373	146	.	16	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	164

APPENDIX TABLE 3.—Counts of selected categories of fish larvae, tabulated by station, EASTROPAC II.—Continued.

STATION NUMBER	<u>Vinciguerria</u> spp.	<u>Cyclothone</u> spp.	<u>Bathylagus nigrigenys</u>	<u>Leuroglossus stilbus urotrianus</u>	<u>Nansenia</u> sp.	<u>Diplophos taenia</u>	<u>Ichthyococcus irregularis</u>	<u>Maurolicus muelleri</u>	<u>Astronesthidae</u>	<u>Bathophilus filifer</u>	<u>Stomias</u> sp.	<u>Evermannellidae</u>	<u>Macroparalepis macrurus</u>	<u>Scopelosauridae</u>	<u>Scomberesocidae</u>	<u>Gempylus serpens</u>	<u>Nealotus tripes</u>	<u>Diplospimus multistriatus</u>	<u>Trichurus lepturus</u>	<u>Tetragnonurus</u> spp.	<u>Trachichthyidae</u>	<u>Balistidae</u>	<u>Ostraciontidae</u>	Total: selected categories
45.375	39	.	3	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	43
45.377	75	.	8	.	.	11	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	95
45.379	797	1	2	.	.	7	.	.	.	.	.	.	.	.	.	4	.	.	.	.	.	1	.	812
45.381	244	.	4	.	.	4	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	253
45.383	18	.	4	.	.	2	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	26
45.385	60	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	61
45.387	428	1	.	.	.	.	.	.	.	3	1	.	.	.	.	.	.	.	.	.	.	.	.	433
CRUISE	46																							
46.002	18	.	2	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	21
46.004	116	.	4	.	.	4	.	.	.	3	.	.	.	.	.	1	.	.	.	.	.	.	.	130
46.006	18	.	1	.	.	1	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	21
46.007	28	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	28
46.009	22	.	1	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	24
46.011	69	.	1	.	.	3	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	75
46.013	47	.	.	.	.	4	.	.	.	5	.	.	.	.	.	.	.	.	.	.	.	.	1	57
46.015	16	.	1	.	.	1	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	19
46.017	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	11
46.019	147	.	1	.	.	1	.	.	.	2	.	.	.	.	.	2	1	.	.	.	.	.	.	154
46.020	78	.	10	.	.	2	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	92
46.022	14	.	1	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	16
46.024	21	6	5	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	33
46.026	131	9	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	145
46.028	154	2	12	.	.	1	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	171
46.030	7	.	8	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	16
46.032	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
46.034	35	5	5	.	.	.	.	.	1	.	.	.	.	.	.	3	.	.	.	.	.	.	.	49
46.036	91	36	7	.	.	.	.	.	1	.	.	.	.	.	.	.	1	.	.	.	.	.	.	136
46.038	4	3	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	10
46.040	19	1	.	.	.	.	.	.	.	.	.	.	.	.	.	2	1	.	.	.	.	.	.	23
46.042	129	4	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	137
46.044	95	.	1	.	.	.	1	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	98
46.046	56	1	1	.	1	.	.	.	.	.	1	.	.	.	.	1	.	.	.	.	.	.	.	61
46.048	53	1	10	.	.	.	.	.	.	.	.	1	1	.	.	2	.	.	.	.	.	.	.	67
46.050	175	6	12	.	.	.	1	1	.	.	.	.	3	.	.	2	.	.	.	.	.	.	.	201
46.052	206	9	7	.	.	.	.	2	.	.	.	8	2	.	.	.	1	.	.	.	.	.	.	235
46.054	177	2	20	.	.	.	.	.	.	.	.	.	1	.	.	.	2	.	.	.	.	.	.	202
46.055	66	4	5	.	.	.	2	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	78
46.057	610	38	10	.	.	.	.	.	.	1	.	2	1	.	.	1	.	.	.	.	.	.	.	665
46.059	480	23	2	.	.	.	.	.	.	1	2	.	.	14	.	.	3	.	.	1	.	.	.	526
46.061	85	7	3	.	3	.	.	6	1	.	.	.	.	10	.	.	.	.	.	1	.	.	.	116
46.063	16	.	2	.	.	.	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	21
46.065	76	15	4	.	.	.	.	.	3	1	.	1	.	.	.	.	.	.	.	.	.	.	.	103
46.067	104	13	5	.	2	.	2	2	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	129
46.069	52	1	22	.	5	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	82
46.071	26	.	14	.	3	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	45
46.075	20	1	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	26
46.077	17	2	1	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	2	.	.	23
46.079	23	.	23	.	1	.	1	6	F	.	.	.	.	.	.	.	.	.	.	.	.	.	.	65
46.082	10	.	17	.	.	.	.	36	4	.	.	.	.	3	7	.	.	.	.	.	.	.	.	74

APPENDIX TABLE 3.—Counts of selected categories of fish larvae, tabulated by station, EASTROPAC II.—Continued.

STATION NUMBER	<u>Vinciguerria</u> spp.	<u>Cyclothone</u> spp.	<u>Bathylagus</u> <u>nigrigenus</u>	<u>Leuroglossus</u> <u>stilbius</u> <u>urotraneus</u>	<u>Nansenia</u> sp.	<u>Diplophos</u> <u>taenia</u>	<u>Ichthyococcus</u> <u>irregularis</u>	<u>Maurolicus</u> <u>muelleri</u>	Astronesthidae	<u>Bathophilus</u> <u>filifer</u>	<u>Stomias</u> sp.	Evermannellidae	<u>Macroparalepis</u> <u>macrurus</u>	Scopelosauridae	Scomberesocidae	<u>Gempylus</u> <u>serpens</u>	<u>Nealotus</u> <u>tripes</u>	<u>Diplospinus</u> <u>multistriatus</u>	<u>Trichiurus</u> <u>lepturus</u>	<u>Tetragonurus</u> spp.	Trachichthyidae	Balistidae	Ostracodontidae	Total: selected categories
46.084	17	1	21	.	6	.	2	19	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	67
46.086	66	2	33	.	2	.	1	169	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	274
46.088	27	7	8	.	1	.	2	24	.	1	.	.	.	1	.	.	1	.	.	.	.	.	.	72
46.090	17	4	4	.	.	.	.	3	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	29
46.092	13	5	3	.	.	.	.	11	1	3	.	.	.	.	.	.	.	.	.	.	.	.	.	36
46.094	145	9	3	.	.	.	2	.	1	.	.	2	1	.	.	.	.	.	.	.	.	.	.	163
46.096	226	21	13	.	.	.	2	.	.	.	.	3	3	.	.	.	2	.	.	.	.	.	.	270
46.098	40	2	2	.	.	.	.	.	.	8	.	.	.	.	.	.	.	.	.	.	.	.	.	52
46.100	6	.	2	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	10
46.102	48	6	3	.	1	.	2	.	.	4	.	.	3	.	.	.	.	.	.	.	.	.	.	67
46.104	46	2	.	.	.	.	.	.	.	1	.	.	1	.	.	1	.	.	.	.	.	.	.	51
46.106	34	7	9	.	.	.	.	.	.	1	.	.	.	.	.	1	.	.	.	.	.	.	.	52
46.108	36	2	27	.	.	.	.	.	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	69
46.110	10	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	15
46.112	75	.	16	.	.	.	.	.	.	1	.	.	.	.	.	.	1	.	.	.	.	.	.	93
46.114	6	.	3	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	10
46.116	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	5
46.118	85	.	3	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	89
46.120	100	.	1	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	103
46.122	29	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	33
46.124	22	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	24
46.126	98	.	10	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	109
46.128	130	.	8	.	.	1	.	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	142
46.130	53	.	11	.	.	.	.	.	.	1	.	.	.	.	.	1	.	.	.	.	.	.	.	66
46.132	26	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	.	35
46.134	12	.	8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	20
46.135	12	.	8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	20
46.137	28	.	24	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1	.	54
46.139	50	1	11	.	.	.	1	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	64
46.141	20	.	18	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	1	.	.	.	.	41
46.143	14	1	10	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1	.	27
46.145	118	1	38	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	157
46.147	41	.	41	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	83
46.149	11	3	22	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	37
46.151	4	4	13	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	22
46.153	163	1	4	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	169
46.155	132	6	6	.	.	.	.	.	.	2	.	.	.	.	.	2	6	.	.	.	.	.	.	156
46.157	24	2	6	.	.	.	1	.	.	.	.	.	2	.	.	4	1	.	.	.	.	.	.	40
46.159	10	1	2	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	15
46.161	35	12	8	.	1	.	.	.	2	.	.	2	.	.	.	4	.	.	.	.	.	.	.	64
46.163	80	4	10	.	.	.	.	4	.	3	.	.	.	.	.	1	1	.	.	.	.	.	.	103
46.165	22	7	16	.	.	.	.	7	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	56
46.167	25	4	37	.	.	.	1	10	.	.	.	.	.	.	.	.	5	.	.	.	.	.	.	82
46.169	149	1	52	.	.	.	1	85	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	290
46.171	13	.	44	.	.	.	1	41	.	1	.	.	.	3	.	.	.	.	.	.	.	.	.	103
46.173	1	.	9	1	.	.	.	14	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	25
46.175	1	.	21	.	.	.	.	74	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	96
46.177	20	5	45	.	.	.	3	5	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	80
46.179	62	1	135	.	.	.	2	24	1	.	.	.	.	1	.	.	.	.	.	1	.	.	.	247
46.181	53	4	132	.	1	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	191
46.183	17	3	47	.	4	.	1	.	3	.	2	.	.	1	.	.	.	.	.	.	.	.	.	78
46.185	90	7	45	.	1	.	2	.	3	.	2	.	.	.	.	.	.	.	.	.	.	.	.	148

APPENDIX TABLE 3.—Counts of selected categories of fish larvae, tabulated by station, EASTROPAC II.—Continued.

STATION NUMBER	<u>Vinciguerria</u> spp.	<u>Cyclothone</u> spp.	<u>Bathylagus</u> <u>nigrigenys</u>	<u>Leuroglossus</u> <u>stilbius</u> <u>urotraneus</u>	<u>Nansenia</u> sp.	<u>Diplophos</u> <u>taenia</u>	<u>Ichthyococcus</u> <u>irregularis</u>	<u>Maurolicus</u> <u>muelleri</u>	Astronesthidae	<u>Bathophilus</u> <u>filifer</u>	<u>Stomias</u> sp.	Evermannellidae	<u>Macroparalepis</u> <u>macrurus</u>	Scopelosauridae	Scomberesocidae	<u>Gempylus</u> <u>serpens</u>	<u>Nealotus</u> <u>tripes</u>	<u>Diplospinus</u> <u>multistriatus</u>	<u>Trichiurus</u> <u>lephurus</u>	<u>Tetragnonurus</u> spp.	Trachichthyidae	Balistidae	Ostraciontidae	Total: selected categories
46.187	39	3	17	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	60
46.189	5	.	5	.	.	.	.	.	.	.	1	.	.	.	.	.	1	.	.	.	.	.	.	15
CRUISE 47																								
47.001	61	2	4	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	11	.	.	.	.	79
47.005	203	3	6	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	5	.	.	.	.	219
47.008	49	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	6	.	.	.	.	.	62
47.011	26	.	3	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	30
47.019	221	13	5	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	19	.	.	.	.	258
47.022	77	2	2	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	13	.	.	.	.	45
47.025	58	.	4	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	63
47.028	117	1	14	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	133
47.032	137	4	15	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	1	.	159
47.034	36	.	7	.	.	.	.	.	.	.	.	.	10	.	.	.	4	.	.	.	.	.	.	57
47.035	70	3	20	.	.	.	.	.	.	1	.	.	3	.	.	3	1	.	.	.	.	.	.	106
47.040	76	.	8	.	.	.	.	7	.	.	.	.	1	2	.	.	7	.	.	.	.	.	.	101
47.049	92	1	26	.	.	.	.	14	2	2	.	.	5	.	.	.	3	.	.	.	.	.	.	145
47.053	94	1	27	.	.	.	1	5	6	.	.	1	59	.	.	.	8	.	3	.	.	.	.	205
47.057	106	3	50	.	.	.	3	3	.	.	.	.	55	.	.	.	47	.	4	.	.	.	.	271
47.061	18	.	11	.	.	.	.	1	.	.	.	.	6	.	.	.	16	.	3	.	.	.	.	55
47.065	91	.	26	4	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	122
47.069	49	.	21	122	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	14	.	.	207
47.070	17	.	12	176	.	.	.	1	.	.	4	.	.	.	1	.	1	.	.	.	21	.	.	233
47.074	14	.	7	294	.	.	.	.	.	.	.	.	.	1	.	.	1	.	.	.	20	.	.	337
47.078	4	.	3	61	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	2	.	.	71
47.082	6	.	1	79	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	86
47.086	11	.	3	527	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	541
47.090	5	.	6	77	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	89
47.094	2	.	1	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	11
47.097	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1
47.099	.	.	.	2	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	3
47.101	.	.	.	1	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	3
47.103	.	.	2	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	3
47.105	5	.	5	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	11
47.107	7	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	11
47.109	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
47.113	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
47.124	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
47.128	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
47.132	8	1	3	.	.	.	.	.	.	.	.	.	1	1	.	.	.	1	.	.	.	.	.	15
47.134	8	.	.	.	.	.	.	.	.	.	.	.	.	19	.	.	.	1	.	.	.	.	.	28
47.137	9	1	3	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	14
47.139	11	.	5	.	.	.	.	.	.	.	.	.	.	4	.	.	.	1	.	.	.	.	.	21
47.141	16	.	13	.	.	.	.	.	.	.	.	.	.	4	.	.	.	1	.	.	.	.	.	34
47.143	2	.	16	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	.	.	.	.	.	22
47.145	14	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	19
47.147	76	1	16	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	.	.	.	.	.	97
47.149	27	.	15	.	.	.	.	.	2	1	.	.	.	.	.	.	.	3	.	.	.	.	.	48
47.151	3	.	4	.	.	.	.	.	.	.	.	.	.	1	.	.	.	5	.	.	.	.	.	13
47.153	9	4	17	.	.	.	.	.	.	.	.	.	.	.	.	.	5	.	.	.	.	.	.	35

APPENDIX TABLE 3.—Counts of selected categories of fish larvae tabulated by station, EASTROPAC II.—Continued.

STATION NUMBER	<u>Vinciguerra</u> spp.	<u>Cyclothone</u> spp.	<u>Bathylagus</u> <u>nigrigenys</u>	<u>Leucoglossus</u> <u>stilbius</u> <u>urotraneus</u>	<u>Nansenia</u> sp.	<u>Diplophos</u> <u>taenia</u>	<u>Ichthyococcus</u> <u>irregularis</u>	<u>Maurollicus</u> <u>muelleri</u>	<u>Astronesthidae</u>	<u>Bathophilus</u> <u>filifer</u>	<u>Stomias</u> sp.	<u>Evermamelidae</u>	<u>Macroparalepis</u> <u>macrurus</u>	<u>Scopelosauridae</u>	<u>Scomberesocidae</u>	<u>Gempylus</u> <u>serpens</u>	<u>Nealobus</u> <u>tripes</u>	<u>Diplompinus</u> <u>multistriatus</u>	<u>Trichiurus</u> <u>lepturus</u>	<u>Tetragonurus</u> spp.	<u>Trachichthyidae</u>	<u>Balistidae</u>	<u>Ostraciontidae</u>	Total selected categories
47.155	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3
47.157	74	3	27	.	.	.	.	.	.	.	.	.	.	.	.	.	1	7	.	.	.	.	.	112
47.159	11	.	14	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	26
47.162	5	.	6	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	12
47.164	37	.	10	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	49
47.166	19	2	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	22
47.168	1	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	5
47.171	38	1	9	.	.	.	.	.	.	1	1	.	.	.	.	.	.	1	.	.	.	.	.	50
47.173	165	1	17	.	.	.	.	.	.	6	6	.	.	.	.	.	.	.	.	.	.	.	.	189
47.175	95	.	15	1	.	.	.	.	.	1	1	.	.	.	2	.	.	.	.	.	.	.	.	114
47.177	100	.	34	123	.	.	.	.	.	69	69	.	.	.	1	.	.	.	.	.	.	.	.	327
47.179	14	.	28	161	.	.	.	.	.	3	3	.	.	.	.	.	.	.	.	.	1	.	.	207
47.181	31	.	15	44	.	.	.	1	.	.	6	.	.	.	.	.	.	.	.	.	.	.	.	97
47.185	30	1	21	119	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	6	.	.	177
47.189	4	.	27	70	.	.	.	.	.	.	.	.	.	1	1	.	.	.	.	.	1	.	.	104
47.193	2	.	.	.	.	.	.	.	.	2	2	.	.	.	.	.	.	.	.	.	.	.	.	4
47.197	7	.	31	92	.	.	1	.	.	.	.	.	.	2	1	.	.	.	.	.	1	.	.	135
47.201	142	4	66	74	.	.	.	2	.	.	.	.	.	2	.	.	.	.	.	.	2	.	.	292
47.205	38	1	125	27	.	.	.	6	.	1	1	.	.	7	.	.	1	.	.	.	.	.	.	207
47.213	415	12	58	.	.	.	2	7	.	1	.	.	36	.	.	1	2	.	.	.	.	.	.	534
47.217	84	1	30	.	.	.	1	0	.	.	.	.	1	13	.	.	2	.	.	.	.	.	.	135
47.221	30	1	36	.	.	.	5	.	.	.	.	.	1	13	.	1	2	.	.	.	.	.	.	83
47.225	146	4	34	.	.	.	.	.	2	.	.	.	7	.	.	3	6	.	.	.	.	.	.	197
47.229	256	16	17	.	.	.	.	.	1	2	.	.	1	.	.	1	4	.	.	.	.	.	.	298
47.233	241	8	14	.	.	.	.	.	1	.	.	.	2	.	.	2	6	.	.	.	.	.	.	274
47.237	16	1	8	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	26
47.240	44	2	3	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	50
47.242	91	3	20	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	115
47.244	124	5	22	.	.	.	.	.	.	.	5	.	.	.	.	1	2	.	7	.	.	.	.	166
47.246	7	1	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	11
47.250	18	.	3	.	.	.	.	.	.	3	3	.	.	.	.	1	1	.	7	.	.	.	.	36
47.254	27	.	8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	.	.	.	.	39
47.258	36	1	3	.	.	.	1	.	.	.	.	.	.	.	.	1	.	.	5	.	.	.	.	47
47.266	15	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	16
47.272	6	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	8
47.276	208	.	45	.	.	.	.	.	.	.	1	.	.	.	.	.	1	.	9	.	.	.	.	264
47.278	53	5	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	.	.	.	.	.	47
47.280	7	1	14	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	24
47.283	4	2	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	10
47.286	12	2	13	.	.	.	1	.	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.	36
47.288	44	.	11	.	.	.	.	.	.	1	.	.	.	.	.	.	2	.	.	.	.	.	.	58
47.290	11	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	16
47.292	27	1	7	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.	.	.	.	.	.	44
47.295	91	9	7	.	.	.	1	.	.	5	.	.	.	.	.	8	4	.	.	.	.	.	.	125
47.297	122	14	17	.	.	.	.	.	1	8	3	.	.	3	.	13	6	.	.	.	.	.	.	187
47.301	53	1	3	.	.	.	.	.	1	5	.	.	1	.	.	6	1	.	.	.	.	.	.	76
47.304	17	4	4	.	.	.	.	.	.	1	.	.	.	.	.	1	1	.	.	.	.	.	.	28
47.306	60	8	15	.	.	.	.	.	1	6	1	.	.	.	.	8	1	.	.	.	.	.	.	100
47.310	142	11	18	.	.	.	.	.	4	22	.	.	2	.	.	10	10	.	.	.	.	.	.	219
47.314	75	4	24	.	.	.	.	.	4	2	5	1	1	12	.	1	4	.	.	.	.	.	.	133
47.316	45	.	23	.	.	.	.	13	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	87
47.322	22	1	59	.	.	.	2	5	.	2	.	.	.	8	.	.	.	.	.	.	.	.	.	101

APPENDIX TABLE 3.—Counts of selected categories of fish larvae, tabulated by station, EASTROPAC II.—Continued.

STATION NUMBER	<u>Vinciguerria</u> spp.	<u>Cyclohone</u> spp.	<u>Bathylagus nigrigenys</u>	<u>Leuroglossus stibius urotraneus</u>	<u>Nansenia</u> sp.	<u>Diplophos taenia</u>	<u>Ichthyococcus irregularis</u>	<u>Maulolicus muelleri</u>	Astronesthidae	<u>Bathophilus filifer</u>	<u>Stomias</u> sp.	Evermannellidae	<u>Macroparalepis macrurus</u>	Scopelosauridae	Scomberesocidae	<u>Cempylus serpens</u>	<u>Nealotus tripes</u>	<u>Diplospinus multistriatus</u>	<u>Trichurus lepturus</u>	<u>Tetragnomus</u> spp.	Trachichthyidae	Ballistidae	Ostraciontidae	Total: selected categories
47.326	33	1	143	9	.	.	6	.	.	.	1	.	.	43	.	.	.	.	.	.	.	.	.	236
47.330	129	5	123	14	.	.	2	11	1	.	10	.	.	16	.	.	.	.	.	.	.	.	.	311
47.334	28	.	45	9	.	.	.	.	.	.	8	.	.	.	.	.	.	.	.	.	.	.	.	89
47.338	19	.	19	5	.	.	.	.	.	.	8	.	.	.	.	.	.	.	.	.	.	.	.	51
47.342	24	.	17	2	.	.	.	.	.	.	1	.	.	3	7	.	.	.	.	.	.	.	.	54
47.345	44	1	26	.	.	.	.	.	.	1	5	.	.	.	.	.	.	.	.	.	.	.	.	77
47.349	61	.	16	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	79
47.351	66	.	69	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	127
47.354	27	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	87
47.357	66	1	14	.	.	.	.	.	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	85
47.359	56	.	10	.	.	.	.	.	.	2	.	.	1	.	.	.	.	.	.	.	.	.	.	69
47.362	4	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7
47.364	7	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	10
47.367	22	2	11	.	.	.	.	.	.	.	.	.	.	.	3	.	.	.	.	.	.	.	.	38
47.369	3	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	8
47.371	7	5	2	.	.	.	.	.	.	1	.	.	.	.	.	.	.	2	.	.	.	.	.	17
47.373	237	2	2	.	.	.	.	.	.	.	.	.	2	.	.	.	.	16	.	.	.	.	.	259
47.376	72	3	9	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	85
47.379	55	.	6	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	66
47.382	103	1	4	.	.	.	.	.	.	3	.	.	.	.	.	.	.	3	.	.	.	.	.	111
47.415	7	2	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	11
47.430	108	1	.	.	.	.	.	.	.	.	.	.	.	.	4	.	.	1	.	.	.	.	.	114
47.432	69	32	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	103
47.436	2	.	2	.	.	.	.	.	.	1	.	.	.	.	22	.	.	1	1	.	.	.	.	29
47.438	34	1	1	.	.	.	.	.	.	2	.	.	.	.	15	.	.	8	3	.	.	.	.	64
47.440	107	2	.	.	.	.	.	.	.	10	.	.	.	.	7	.	3	.	.	.	.	.	.	129
47.443	17	.	1	.	.	.	.	.	.	2	.	.	.	.	6	.	.	.	.	.	.	.	.	26
47.446	4	.	2	.	.	.	.	.	.	1	.	.	.	.	7	.	.	.	.	.	.	.	.	14
47.450	76	9	20	.	.	.	.	.	.	5	.	.	.	.	37	.	2	.	.	.	.	.	.	149
47.454	21	3	41	.	1	.	.	.	.	.	1	.	.	.	1	.	.	.	.	.	.	.	.	68
47.458	5	.	42	.	.	.	.	.	1	.	2	.	.	.	.	.	.	.	.	1	.	.	.	52
47.462	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
47.466	6	.	7	.	1	.	.	2	.	.	.	.	.	26	.	.	.	.	.	.	.	.	.	42
47.470	3	.	6	.	.	.	107	.	.	.	.	.	.	3	.	.	.	.	.	.	.	.	.	119
47.478	26	1	6	.	.	.	9	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	45
47.486	30	2	11	.	.	.	5	.	.	.	.	.	.	.	.	2	3	.	.	.	.	.	.	53
47.490	14	.	13	.	.	.	3	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	37
47.494	10	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	12
47.498	65	6	1	.	1	.	2	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	78
47.501	148	17	13	.	.	.	.	.	.	1	.	.	.	.	.	2	3	.	.	.	.	.	.	184
47.504	49	9	25	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	79
47.507	75	2	6	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	85
47.509	64	.	26	.	2	.	1	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	93
47.511	2	.	11	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	13
47.513	3	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4
47.515	9	2	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	18
47.517	36	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	37
47.520	80	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	83
47.523	30	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	37
47.525	10	.	6	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	16
47.527	132	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	135

APPENDIX TABLE 4.—Summary of occurrences and numbers of larvae of 23 categories, limited in distribution to a broad coastal band or around offshore islands or banks.

STATION NUMBER	<u>Engraulis ringens</u>	<u>Gobiidae</u>	<u>Albula vulpes</u>	<u>Etmeneus acuminatus</u>	<u>Opisthonema sp.</u>	<u>Sardinops sagax</u>	<u>Engraulidae (other)</u>	<u>Synodontidae</u>	<u>Bothus leopardinus</u>	<u>Citharichthys spp.</u>	<u>Cyclosetta sp.</u>	<u>Syngnathus ovale</u>	<u>Symphurus spp.</u>	<u>Carangidae</u>	<u>Eucinostomus sp.</u>	<u>Labridae</u>	<u>Mugilidae</u>	<u>Polynemidae</u>	<u>Pomacentridae</u>	<u>Sciaenidae</u>	<u>Scorpaenidae</u>	<u>Serranidae</u>	<u>Carapidae</u>	Total: 23 categories
45.339	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1
45.343	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	1	.	.	1
45.350	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1
45.358	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1
45.360	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	1	.	.	.	.	1	.	.	4
45.362	.	.	.	.	.	.	1	.	.	.	.	2	1	1	.	1	.	2	.	.	.	1	.	16
45.365	.	31	.	.	.	.	11	1	1	.	.	2	4	11	.	.	.	19	.	10	.	.	.	90
45.367	.	5	.	.	.	.	2	.	1	.	.	.	.	2	.	.	.	.	.	.	.	3	.	13
45.369	.	20	.	.	.	.	1	.	.	.	.	4	1	10	.	2	.	.	6	.	.	9	.	53
45.371	.	1	.	.	.	.	.	.	.	.	.	4	.	.	.	2	.	.	.	.	.	.	.	7
45.373	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	5	.	.	.	.	1	.	.	8
45.375	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	1	.	.	.	.	.	.	.	2
45.377	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	6	.	.	.	.	5	.	.	11
45.379	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	1
45.381	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	2
CRUISE 46																								
46.002	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1
46.004	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	1	.	.	.	.	.	.	.	2
46.006	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1
46.007	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1
46.009	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	2
46.011	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1	.	.	.	2
46.042	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1
46.052	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	.	.	.	3
46.059	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	1
46.082	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	.	.	1
46.108	.	.	.	.	.	.	.	.	1	.	.	2	.	.	.	.	.	.	.	.	.	.	.	3
46.110	.	.	.	.	.	.	.	4	.	.	.	8	.	.	.	.	.	.	.	.	.	.	.	12
46.112	.	2	.	.	.	.	.	22	.	.	13	3	.	.	.	.	.	.	.	.	.	.	.	45
46.114	.	.	.	.	.	.	.	2	.	.	1	1	.	.	.	1	.	.	.	.	.	.	.	5
46.116	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	1
46.118	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1
46.120	.	1	.	.	.	.	.	1	.	.	.	3	1	.	.	2	.	.	.	.	.	.	.	8
46.122	.	.	.	.	.	.	.	1	.	.	.	2	.	.	.	.	.	.	.	2	.	.	.	5
46.124	.	.	.	.	.	.	.	.	.	.	1	1	2	.	.	.	.	.	.	.	.	.	.	4
46.126	.	4	.	.	.	.	.	5	.	.	.	3	.	1	.	1	.	1	.	.	.	.	.	15
46.128	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	3
46.130	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	2
46.132	.	.	.	.	.	.	.	.	.	.	.	1	1	1	.	.	.	.	.	1	.	.	.	4
46.134	.	.	.	.	1	.	2	1	.	.	10	6	7	.	.	.	.	.	45	18	1	.	.	91
46.135	.	2	.	.	.	1	1	1	.	11	1	6	45	.	.	.	.	4	.	48	23	.	.	143
46.137	.	12	.	.	.	.	5	.	.	13	13	76	2	.	.	.	.	.	.	32	4	.	.	276
46.139	.	.	.	.	.	.	.	.	.	.	2	3	1	.	.	.	.	.	.	1	.	.	.	9
46.141	.	.	.	.	.	.	.	.	.	.	2	2	.	.	.	.	.	.	.	3	.	.	.	7
46.147	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1	.	.	.	2	.	.	.	4
46.149	.	.	.	.	.	.	.	2	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	4
46.151	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	1
46.153	.	1	.	.	.	.	.	1	.	.	.	14	.	.	.	.	.	.	.	.	.	.	.	16
46.155	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
46.157	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1
46.163	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1
46.165	.	.	.	.	.	.	.	.	.	.	.	1	.	1	.	.	.	.	.	1	.	.	.	3

APPENDIX TABLE 4.—Summary of occurrences and numbers of larvae of 23 categories, limited in distribution to a broad coastal band or around offshore islands or banks.—*Continued.*

STATION NUMBER	<u>Engraulis ringens</u>	Gobiidae	<u>Albula vulpes</u>	<u>Etrumeus acuminatus</u>	<u>Opisthonema</u> sp.	<u>Sardinops sagax</u>	Engraulidae (other)	Synodontidae	<u>Bothus leopardinus</u>	<u>Citharichthys</u> spp.	<u>Cyclopsetta</u> sp.	<u>Syacium ovale</u>	<u>Symphurus</u> spp.	Carangidae	<u>Eucinostomus</u> sp.	Labridae	Mugilidae	Polynemidae	Pomacentridae	Sciaenidae	Scorpaenidae	Serranidae	Carapidae	Total: 23 categories
46.171	.	2	.	3	.	64	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	69
46.173	.	2	.	.	.	2	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	5
46.175	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2
46.177	.	.	.	.	.	20	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	21
46.179	.	3	.	1	.	81	.	.	.	21	.	.	.	.	.	1	.	.	.	.	.	.	.	107
46.181	.	.	.	.	.	6	.	.	.	8	.	.	1	.	.	.	.	.	.	.	.	.	.	20
46.185	.	.	.	.	.	.	.	.	.	4	.	.	1	.	.	.	.	.	.	.	.	.	.	5
46.187	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	5	.	6
CRUISE 47																								
47.001	.	9	.	.	.	.	.	4	.	.	.	3	3	4	.	.	.	.	.	.	1	.	.	24
47.005	.	46	.	.	.	.	.	5	.	.	11	2	2	2	.	.	.	.	.	.	3	.	.	69
47.008	.	35	.	.	.	.	2	3	5	.	2	3	1	1	.	.	.	.	.	.	3	1	.	56
47.011	.	11	.	.	.	.	.	.	.	.	1	.	1	11	.	.	.	.	.	.	1	.	.	25
47.019	.	36	2	.	.	.	5	7	1	.	3	5	9	5	4	4	7	2	2	.	4	7	.	103
47.022	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	2	.	3
47.025	.	5	.	.	.	.	.	.	.	1	.	.	.	.	.	1	.	.	1	.	.	.	.	8
47.028	.	24	.	.	.	.	.	.	.	.	3	12	.	.	.	.	.	.	.	.	1	.	.	40
47.032	.	6	.	.	.	.	.	.	.	.	4	2	.	.	.	.	.	.	.	.	5	.	.	17
47.034	.	2	.	.	.	.	.	.	.	.	3	9	3	.	.	.	.	.	.	.	10	.	.	27
47.035	.	.	.	.	.	.	.	.	.	.	.	1	5	.	.	.	.	.	.	.	6	.	.	12
47.040	.	19	.	.	.	.	28	3	.	2	3	1	6	7	6	3	.	1	1	10	17	.	.	107
47.049	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
47.053	.	.	.	.	.	.	1	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	2
47.057	.	5	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1	.	.	7
47.061	.	2	.	.	.	.	.	1	.	.	.	.	1	.	.	.	.	.	.	.	2	.	.	6
47.065	.	3	.	.	.	.	.	.	.	1	1	.	4	4	.	1	2	.	1	.	1	.	1	19
47.069	1	6	.	.	.	.	.	1	.	.	1	3	2	.	.	1	.	.	.	.	.	.	.	15
47.070	.	2	.	.	.	.	.	.	.	2	.	1	1	.	.	.	2	.	.	.	.	.	.	8
47.074	.	13	.	.	.	.	.	.	.	9	.	1	1	.	.	.	.	.	.	1	1	3	.	29
47.078	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1	.	.	2
47.082	26	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	26
47.086	127	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	127
47.090	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
47.097	250	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	252
47.099	48	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	11	.	.	.	59
47.101	222	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	222
47.103	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
47.105	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
47.107	4	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	7
47.109	293	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	293
47.113	35	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	35
47.124	99	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	99
47.128	96	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	96
47.132	43	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	43
47.139	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4
47.141	12	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	12
47.147	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
47.162	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
47.173	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2
47.175	13	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	13
47.177	4	5	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	10

APPENDIX TABLE 4.—Summary of occurrences and number of larvae of 23 categories, limited in distribution to a broad coastal band or around offshore islands or banks.—Continued.

STATION NUMBER	<u>Engraulis ringens</u>	<u>Gobiidae</u>	<u>Albula vulpes</u>	<u>Etrumeus acuminatus</u>	<u>Opisthonema sp.</u>	<u>Sardinops sagax</u>	<u>Engraulidae (other)</u>	<u>Synodontidae</u>	<u>Bothus leopardinus</u>	<u>Citharichthys spp.</u>	<u>Cyclosetta sp.</u>	<u>Syngnathus ovale</u>	<u>Syngnathus spp.</u>	<u>Carangidae</u>	<u>Eucinostomus sp.</u>	<u>Labridae</u>	<u>Mugilidae</u>	<u>Polynemidae</u>	<u>Pomacentridae</u>	<u>Sciaenidae</u>	<u>Scorpaenidae</u>	<u>Serranidae</u>	<u>Carapidae</u>	Total: 23 categories
47.179	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
47.181	1	3	.	.	.	.	.	.	.	1	.	.	.	.	.	1	.	.	.	.	3	1	.	10
47.185	13	1	.	.	.	.	.	1	.	.	1	.	.	.	.	.	.	.	1	1	1	1	.	19
47.189	1	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	1	.	1	2
47.197	9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	1	11
47.201	.	3	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	1	.	.	2
47.229	.	1	.	.	.	.	.	.	1	.	.	1	.	.	.	.	.	.	.	.	2	.	.	7
47.233	.	1	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	4	.	.	6
47.237	.	1	.	.	.	.	.	.	.	.	.	1	1	.	.	.	.	.	.	.	2	.	.	5
47.240	.	5	.	.	.	.	.	.	2	.	.	.	.	.	.	1	.	.	.	.	1	.	.	9
47.242	.	4	.	.	.	.	.	.	.	.	.	2	2	.	.	.	.	.	.	.	1	.	.	7
47.244	.	.	.	.	.	.	.	.	1	.	.	2	1	.	.	.	.	.	.	.	1	.	.	5
47.246	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
47.250	.	.	.	.	.	.	.	.	.	.	.	1	2	.	.	.	.	.	.	.	.	.	.	3
47.254	.	3	.	.	.	.	.	.	.	.	.	1	1	.	.	1	.	2	.	.	.	1	.	8
47.258	.	5	.	.	.	.	.	4	10	.	.	3	4	16	.	.	2	.	.	1	36	3	.	84
47.268	.	.	.	.	.	.	.	1	1	2	.	9	.	.	.	.	2	.	.	5	5	3	.	21
47.272	.	1	.	.	.	.	.	.	.	1	.	4	2	3	.	.	.	.	.	2	2	.	.	13
47.276	.	.	.	.	.	.	.	.	.	.	.	4	2	.	.	3	.	.	.	.	.	.	.	17
47.278	.	.	.	.	.	.	.	.	.	.	.	1	1	.	.	.	.	.	.	.	2	.	.	3
47.283	.	1	.	.	.	.	.	.	.	.	.	1	1	.	.	.	.	.	.	.	.	.	.	3
47.286	.	1	.	.	.	.	.	.	1	.	.	1	5	.	.	1	.	.	.	.	.	.	.	9
47.288	.	1	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1	3
47.290	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1
47.292	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1
47.295	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1
47.301	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	1
47.304	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	.	2
47.306	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	4	.	.	5
47.310	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	3	.	5
47.314	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	2
47.322	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1
47.330	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1
47.334	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1
47.349	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1
47.357	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1
47.436	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
47.446	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1
47.450	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1
47.466	.	.	.	.	.	2	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	3
47.470	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	1	.	.	2
47.501	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	1
47.504	.	.	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	2
47.507	.	.	.	.	.	.	.	.	.	.	.	3	1	1	.	.	.	.	.	.	.	.	.	5
47.509	.	.	.	.	.	.	.	.	3	.	.	2	.	.	.	.	.	.	.	.	.	.	.	5
47.511	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	1	.	.	2
47.513	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1
47.515	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	1
47.517	.	1	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	3
47.520	.	8	.	.	.	.	.	.	.	.	.	13	8	.	.	1	.	.	.	13	.	.	.	43
47.523	.	.	.	.	.	.	.	.	.	.	.	1	2	.	.	1	.	.	.	2	1	.	.	7
47.525	.	.	.	.	.	.	.	.	1	.	.	3	4	.	.	.	.	.	.	.	1	.	.	9
47.527	.	7	7	.	83	.	1	23	36	.	1	180	142	69	3	.	.	.	.	15	1	.	.	568

APPENDIX TABLE 5.—Numbers and kinds of eel leptocephali (Anguilliformes) obtained on the second multivessel EASTROPAC survey (EASTROPAC II), tabulated by family for all positive hauls.

STATION NUMBER	Eel leptocephali	Congridae	Moringuidae	Muraenidae	Nemichthyidae	Ophichthidae	Serrivomeridae	Xenocoelidae	Family unknown	STATION NUMBER	Eel leptocephali	Congridae	Moringuidae	Muraenidae	Nemichthyidae	Ophichthidae	Serrivomeridae	Xenocoelidae	Family unknown
45 .018	2	.	.	.	2	.	.	.	.	46 .157	1	.	.	.	1	.	.	.	.
45 .023	1	.	.	.	1	.	.	.	.	46 .161	1	.	.	.	.	.	.	.	1
45 .030	1	.	.	.	.	.	1	.	.	46 .165	1	.	.	.	1	.	.	.	.
45 .058	1	.	.	.	.	.	1	.	.	46 .169	1	.	.	.	1	.	.	.	.
45 .063	1	.	.	.	.	.	.	.	1	46 .177	1	.	.	.	.	.	.	1	.
45 .065	2	.	.	.	.	.	2	.	.	47 .001	3	1	.	.	.	2	.	.	.
45 .067	2	.	.	.	.	.	2	.	.	47 .008	1	1	.	.	.	.	.	.	.
45 .071	1	.	.	.	.	.	1	.	.	47 .011	3	2	.	.	1	.	.	.	.
45 .073	1	.	.	.	.	.	.	.	1	47 .019	11	4	.	2	.	5	.	.	.
45 .140	2	.	.	.	1	.	.	.	1	47 .028	2	.	1	.	1	.	.	.	.
45 .313	1	.	.	.	.	.	1	.	.	47 .032	1	.	1	.	.	.	.	.	.
45 .362	1	1	.	.	.	.	.	.	.	47 .035	1	1	.	.	.	.	.	.	.
45 .365	12	4	1	.	.	7	.	.	.	47 .040	6	.	.	.	.	3	.	3	.
45 .367	3	1	.	.	.	.	.	.	2	47 .049	2	.	.	.	.	2	.	.	.
45 .371	1	.	.	.	.	1	.	.	.	47 .053	2	.	.	.	.	.	1	1	.
45 .379	1	.	.	.	1	.	.	.	.	47 .069	1	.	.	.	1	.	.	.	.
46 .032	1	1	.	.	.	.	.	.	.	47 .070	1	.	.	.	1	.	.	.	.
46 .034	1	.	.	.	.	.	.	1	.	47 .107	1	.	.	.	1	.	.	.	.
46 .046	2	.	.	.	.	.	.	.	2	47 .179	1	.	.	.	1	.	.	.	.
46 .065	1	1	.	.	.	.	.	.	.	47 .197	1	.	.	.	1	.	.	.	.
46 .077	1	1	.	.	.	.	.	.	.	47 .217	1	1	.	.	.	.	.	.	.
46 .086	2	.	.	.	1	.	.	1	.	47 .229	1	1	.	.	.	.	.	.	.
46 .098	1	.	.	.	.	.	.	.	1	47 .233	1	.	.	.	1	.	.	.	.
46 .106	1	.	.	.	1	.	.	.	.	47 .242	1	.	.	.	1	.	.	.	.
46 .108	1	.	.	.	1	.	.	.	.	47 .244	1	1	.	.	.	.	.	.	.
46 .110	2	.	.	1	.	1	.	.	.	47 .254	1	1	.	.	.	.	.	.	.
46 .112	1	.	.	.	1	.	.	.	.	47 .258	4	2	.	1	.	.	.	1	.
46 .114	1	.	.	1	.	.	.	.	.	47 .268	1	.	.	.	1	.	.	.	.
46 .120	1	.	.	.	.	1	.	.	.	47 .276	1	1	.	.	.	.	.	.	.
46 .122	1	1	.	.	.	.	.	.	.	47 .283	1	.	.	.	1	.	.	.	.
46 .124	2	.	.	.	.	2	.	.	.	47 .286	1	.	.	1	.	.	.	.	.
46 .128	1	1	.	.	.	.	.	.	.	47 .297	3	1	.	.	.	.	.	2	.
46 .130	2	2	.	.	.	.	.	.	.	47 .304	2	.	.	.	1	.	.	1	.
46 .134	2	.	.	.	.	2	.	.	.	47 .314	3	2	.	1	.	.	.	.	.
46 .135	3	.	.	.	.	3	.	.	.	47 .438	2	.	.	.	2	.	.	.	.
46 .137	1	1	.	.	.	.	.	.	.	47 .478	1	.	.	.	.	1	.	.	.
46 .139	4	2	.	.	.	2	.	.	.	47 .504	1	.	.	.	1	.	.	.	.
46 .143	1	.	.	.	.	1	.	.	.	47 .509	1	1	.	.	1	.	.	1	.
46 .145	2	1	.	1	.	.	.	.	.	47 .525	3	3	.	.	.	.	.	.	.
46 .153	1	.	.	.	1	.	.	.	.	47 .527	7	2	.	.	5	.	.	.	.
46 .155	1	.	.	.	1	.	.	.	.										

APPENDIX TABLE 6.—Numbers and kinds of lophiiform larvae obtained on the second multivessel EASTROPAC survey (EASTROPAC II), tabulated by family for all positive hauls.

STATION NUMBER	Caulophrynidae	Centroprygnidae	Ceratiidae	Gigantactinidae	Himantolophidae	Linophrynidae	Melanocetidae	Oenirodidae	Unidentified Ceratioidei	Antennariidae	Lophidae
45 .037	.	.	.	.	.	1	.	.	.	.	.
45 .039	.	.	.	.	.	.	.	.	1	.	.
45 .044	.	.	.	.	.	.	.	.	.	.	.
45 .046	.	.	.	1	.	.	.	.	.	.	.
45 .048	.	.	.	.	.	.	.	1	1	.	.
45 .050	.	.	.	.	1	.	.	.	1	.	.
45 .051	.	.	.	.	.	.	.	1	1	.	.
45 .053	.	.	.	.	.	.	.	1	.	.	.
45 .054	.	.	.	.	.	.	.	1	.	.	.
45 .056	.	.	.	1	.	.	1	1	.	.	.
45 .058	.	.	.	1	1	.	.	1	.	.	.
45 .060	.	.	.	.	.	.	.	1	.	.	.
45 .063	.	.	.	1	.	.	1	.	.	.	.
45 .065	.	.	.	.	.	.	1	.	3	.	.
45 .067	.	.	.	2	2	.	.	1	.	.	.
45 .078	.	.	.	.	.	.	.	1	1	.	.
45 .110	.	.	.	.	.	.	.	1	.	.	.
45 .127	.	.	.	.	.	.	.	1	.	.	.
45 .131	.	.	.	1	.	.	.	.	.	.	.
45 .171	.	.	.	1	.	.	.	.	.	.	.
45 .175	.	.	.	.	1	.	.	.	.	.	.
45 .309	.	.	.	.	1	.	.	.	.	.	.
45 .319	.	.	.	.	.	.	.	1	1	.	.
45 .321	.	.	.	.	.	.	.	.	1	.	.
45 .325	.	1	.	.	.	.	.	.	1	.	.
46 .028	1	.	.	.	.	.	1	.	.	.	.
46 .034	.	.	.	.	.	.	.	1	1	.	.
46 .044	.	.	.	.	.	.	.	.	1	.	.
46 .046	.	.	.	1	1	.	.	2	.	.	.
46 .048	.	.	.	.	.	.	1	.	.	.	.
46 .052	.	.	.	.	.	.	.	1	.	.	.
46 .057	.	.	.	.	.	.	.	1	.	.	.
46 .059	.	.	.	.	.	.	.	.	1	.	.
46 .086	.	.	.	.	.	.	.	1	.	.	.
46 .088	.	.	.	.	.	.	1	.	.	.	.
46 .094	.	.	.	.	.	.	.	.	1	.	.
46 .098	.	.	1	.	.	.	.	.	.	.	.
46 .100	.	.	.	1	.	.	.	.	.	.	.
46 .102	.	.	.	1	.	.	.	2	.	.	.
46 .104	.	.	.	.	.	.	.	.	1	.	.
46 .108	.	.	.	.	.	.	1	.	.	.	.
46 .110	.	.	.	.	.	.	1	.	.	.	.
46 .112	.	.	.	.	.	.	.	2	.	.	.
46 .114	.	.	.	.	.	.	1	.	.	.	.
46 .122	.	.	.	.	.	.	.	.	1	.	.
46 .126	.	.	.	.	.	.	4	.	.	.	.
46 .128	.	.	.	.	.	.	2	.	1	.	.
46 .132	.	.	.	.	.	.	.	.	.	1	.
46 .139	.	.	.	.	.	.	1	.	.	.	.
46 .145	.	.	.	.	.	.	.	.	.	.	1
46 .153	.	.	.	.	.	.	.	1	.	.	.
46 .155	.	.	.	.	.	.	.	1	.	.	.
46 .159	.	.	.	.	.	.	1	3	.	.	.
46 .161	.	.	2	1	.	.	.	1	.	.	.
46 .163	.	.	.	.	.	.	2	1	.	.	.
46 .165	1	.	.	1	.	.	1	.	.	.	.
46 .167	.	.	.	.	.	.	.	1	.	.	.
STATION NUMBER	Caulophrynidae	Centroprygnidae	Ceratiidae	Gigantactinidae	Himantolophidae	Linophrynidae	Melanocetidae	Oenirodidae	Unidentified Ceratioidei	Antennariidae	Lophidae
46 .169	.	.	.	.	.	.	.	.	.	.	.
47 .001	.	.	.	.	.	1	.	.	.	.	.
47 .005	.	.	.	.	.	.	.	.	.	1	.
47 .008	.	.	.	.	.	2	.	1	.	.	.
47 .011	.	.	.	.	.	3	.	.	.	.	.
47 .019	.	.	.	.	.	.	2	2	.	.	.
47 .025	.	.	.	.	.	.	.	2	.	.	.
47 .028	.	.	.	.	.	.	4	2	.	.	.
47 .032	.	.	.	.	.	.	.	2	.	.	.
47 .034	.	.	.	.	.	.	.	1	.	.	.
47 .035	.	.	.	.	.	1	.	.	2	.	.
47 .040	.	.	1	.	.	.	.	.	.	.	.
47 .049	.	.	.	.	.	.	.	1	.	.	.
47 .053	.	.	1	.	.	.	.	5	.	.	.
47 .057	.	.	.	1	.	.	.	.	.	.	.
47 .061	.	.	.	.	.	.	.	1	.	.	.
47 .074	.	.	.	.	.	2	.	.	.	.	.
47 .090	.	.	.	.	.	1	.	.	.	.	.
47 .141	.	.	.	.	.	1	.	.	.	.	.
47 .177	.	.	.	.	.	1	.	.	.	.	.
47 .197	.	.	.	.	.	1	.	.	.	.	.
47 .201	.	.	.	.	.	1	.	.	.	.	.
47 .213	.	.	.	.	.	.	.	.	4	.	.
47 .217	.	.	.	.	.	.	.	.	4	.	.
47 .225	.	.	.	.	.	.	.	.	3	2	.
47 .229	.	.	.	.	1	1	.	1	1	.	.
47 .240	.	.	.	.	.	.	.	.	1	.	.
47 .242	.	.	.	.	2	1	.	.	.	.	.
47 .244	.	.	.	.	.	4	6	.	.	.	.
47 .246	.	.	.	.	.	1	1	.	.	.	.
47 .250	.	.	.	.	.	1	2	.	.	.	.
47 .254	.	.	.	.	.	.	.	.	1	.	.
47 .268	.	.	.	.	.	1	.	.	.	.	.
47 .276	.	.	.	.	.	1	.	.	.	.	.
47 .283	.	.	.	.	.	.	1	.	.	.	.
47 .286	.	.	.	.	.	.	2	.	.	.	.
47 .292	.	.	.	.	.	.	.	1	.	.	.
47 .295	.	.	.	.	.	.	.	4	.	.	.
47 .297	.	.	.	.	.	.	.	1	.	.	.
47 .306	.	.	.	.	.	.	.	.	.	4	.
47 .310	.	.	.	6	2	1	5	2	.	.	.
47 .322	.	.	3	.	.	1	1	.	.	.	.
47 .326	.	.	.	.	4	.	.	.	.	.	.
47 .351	.	.	.	.	2	.	.	.	.	.	.
47 .357	.	.	.	.	.	1	.	.	.	.	.
47 .450	.	.	.	1	.	.	.	.	.	.	.
47 .454	.	.	.	.	.	.	.	.	1	.	.
47 .486	.	.	.	1	1	.	.	2	.	.	.
47 .490	.	.	.	4	.	.	.	2	1	.	.
47 .498	.	.	.	.	1	.	.	.	.	.	.
47 .501	.	.	.	.	.	.	1	.	.	.	.
47 .504	.	.	.	.	.	.	1	.	.	.	.
47 .507	.	.	.	.	.	.	1	.	.	.	.
47 .511	.	.	.	.	.	.	1	.	.	.	.
47 .513	.	.	.	.	.	.	1	.	.	.	.
47 .523	.	.	.	.	.	.	1	.	.	.	.
47 .525	.	.	.	.	.	.	1	.	.	.	.

APPENDIX TABLE 7A.—Counts of fish larvae, tabulated by family, for all stations occupied by *Oceanographer* on zig-transect.

STATION NUMBER	Myctophidae	Gonostomatidae	Bathylagidae	Clupeidae	Engraulidae	Sternoptychidae	Chauliodontidae	Idiacanthidae	Other Stomiatoidei	Paralepididae	Scopelosauridae	Melamphaidae	Bregmacerotidae	Exocoetidae	Bramidae	Chiasmodontidae	Coryphaenidae	Nomeidae	Scombridae	Other Identified Larvae	Unidentified Larvae	Disintegrated Larvae	Total Fish Larvae
OP .001	8	.	.	.	7	.	1	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	17
OP .002	2	.	.	.	200	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	202
OP .003	4	.	.	.	74	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	79
OP .005	32	9	3	.	.	.	1	.	.	.	.	2	.	.	.	.	.	3	.	.	1	2	52
OP .007	50	19	11	.	.	.	1	.	.	.	.	.	.	.	.	2	.	3	.	.	.	2	88
OP .009	41	9	12	.	.	1	1	.	.	.	.	18	.	.	.	8	.	1	.	.	.	.	91
OP .011	50	19	6	.	.	.	3	.	.	.	.	4	.	.	.	2	.	7	.	5	1	9	106
OP .013	70	22	20	.	.	.	11	.	.	.	.	3	.	.	.	2	.	3	.	1	.	.	132
OP .015	46	15	24	.	.	.	5	.	.	.	.	1	.	.	2	1	.	.	.	2	2	2	98
OP .017	13	1	1	.	.	5	.	.	.	.	2	.	.	.	.	2	.	1	.	2	.	2	29
OP .019	20	10	8	.	.	16	1	.	1	.	.	1	.	.	1	.	.	3	.	.	3	.	64
OP .021	10	7	4	.	.	6	.	.	.	.	.	2	.	.	.	.	.	4	.	.	1	2	36
OP .023	251	53	15	.	.	61	2	.	1	.	.	5	.	.	.	3	.	.	.	.	.	2	393
OP .025	206	31	8	.	.	19	.	.	2	.	.	3	.	.	.	1	.	3	.	1	.	1	275
OP .027	248	110	111	.	.	41	.	3	8	14	.	9	.	.	.	1	.	13	.	1	.	30	589
OP .029	168	146	153	.	.	26	.	1	18	34	.	5	.	.	1	.	.	7	.	2	1	56	623
OP .032	321	154	213	.	1	54	2	3	17	79	2	16	.	.	.	3	.	12	.	2	1	12	886
OP .036	543	2047	487	.	1	36	.	.	18	57	.	12	.	.	.	.	10	.	2	.	.	25	3238
OP .040	113	126	176	.	.	6	.	.	14	9	.	3	.	.	.	1	.	11	.	1	.	8	468
OP .044	100	64	38	.	.	5	.	1	12	7	.	5	.	.	.	8	.	7	.	17	.	1	265
OP .048	230	103	119	.	.	47	.	24	54	20	13	.	.	.	2	1	.	4	.	18	.	97	732
OP .052	101	52	51	.	.	12	.	.	1	6	34	3	.	.	2	1	.	12	.	14	5	20	315
OP .056	62	20	108	.	.	4	.	1	5	40	26	10	.	.	1	.	1	3	.	5	5	30	321
OP .060	43	26	65	.	.	8	.	1	8	8	5	7	.	3	.	2	1	1	.	2	2	3	185
OP .064	387	51	96	.	.	17	.	.	17	26	21	17	.	.	.	2	1	3	.	7	.	10	655
OP .068	119	40	54	.	.	34	.	.	4	16	11	7	.	.	.	6	.	.	.	12	.	3	306
OP .072	109	7	30	.	.	13	.	1	.	9	1	4	.	.	1	4	.	.	.	4	.	4	187
OP .076	86	22	18	.	.	8	.	.	7	18	1	6	.	.	.	3	1	.	.	3	1	5	180
OP .080	127	67	49	.	.	20	.	.	5	13	2	8	.	.	1	2	.	8	.	1	.	4	307
OP .084	105	12	46	.	.	7	.	1	5	19	.	8	.	.	.	1	.	1	.	3	.	14	222
OP .088	70	28	34	.	.	29	.	1	2	38	.	3	.	.	.	3	.	2	.	3	1	7	221
OP .092	17	6	28	.	.	2	.	.	2	7	.	1	.	.	.	1	.	1	.	9	.	1	75
OP .096	64	7	6	.	.	15	.	.	2	19	2	.	.	.	.	.	.	.	.	2	5	2	124
OP .100	92	4	6	.	.	.	.	.	2	5	4	.	.	.	.	.	.	.	.	1	.	.	114
OP .104	60	16	2	7	.	3	.	2	7	3	.	1	.	.	.	.	.	.	.	2	3	3	109
OP .108	95	44	31	.	.	7	.	7	6	28	3	2	.	.	1	.	.	.	.	1	4	6	235
OP .112	320	100	75	.	.	6	.	.	1	11	4	15	.	.	1	1	.	4	.	8	.	6	552
OP .116	383	123	43	.	.	18	.	.	.	23	2	11	.	.	3	.	.	2	.	7	1	5	621
OP .120	110	6	6	.	.	27	.	1	.	2	.	5	.	.	.	.	.	.	.	3	2	3	165
OP .124	296	3	4	.	.	67	2	1	1	.	.	3	.	.	.	.	.	4	.	4	.	.	386
OP .128	1325	181	20	.	.	133	3	2	4	5	.	4	.	1	.	.	.	2	.	5	1	11	1697
OP .132	1454	229	15	.	.	115	3	.	5	5	.	3	.	.	.	.	1	8	.	7	1	10	1856
OP .136	343	14	4	.	.	17	.	1	1	.	.	.	.	5	.	.	.	5	3	.	.	12	408
OP .138	411	9	15	.	.	54	3	.	3	.	5	.	.	.	.	.	.	4	2	1	.	3	510
OP .155	372	37	52	.	.	20	1	.	2	.	.	.	.	.	1	1	1	2	3	.	.	25	522
OP .160	220	152	27	.	.	11	7	.	4	.	.	2	.	5	3	2	1	5	3	33	.	35	510
OP .162	255	155	6	.	.	.	.	.	.	.	.	.	.	.	.	.	15	48	31	1	.	5	525
OP .164	19	10	1	.	.	3	.	.	.	.	.	1	.	.	.	.	9	11	2	.	4	61	
OP .166	4	2	1	.	.	3	.	.	.	.	.	2	.	.	.	.	.	2	.	3	.	1	18
OP .168	131	18	62730	477	.	.	.	.	.	.	.	2	470	.	.	.	.	.	13	704	11	5	4567

APPENDIX TABLE 7B.—Myctophid larvae, tabulated by genus or species, stations occupied by *Oceanographer* on zig-transect.

STATION NUMBER	<u>Bentosema pterota panamense</u>	<u>Ceratoscopelus townsendi</u>	<u>Diaphus</u> spp.	<u>Diogenichthys laternatus</u>	<u>Goniichthys tenuiculus</u>	<u>Hygophum atratum</u>	<u>Hygophum proximum</u>	<u>Lampadena</u> spp.	<u>Lampanyctus</u> spp.	<u>Lepidophanes</u> sp.	<u>Lobianchia</u> sp.	<u>Loweina rara</u>	<u>Myctophum aurolateratum</u>	<u>Myctophum nitidulum</u>	<u>Myctophum</u> sp.	<u>Notolycnus valdiviae</u>	<u>Notoscopelus resplendens</u>	<u>Protomyctophum</u> sp.	<u>Symbolophorus evermanni</u>	<u>Triphoturus</u> spp.	Unidentified Myctophids	Disintegrated Myctophids	Total Myctophids
OP .001	.	.	.	.	.	.	.	.	6	.	.	.	.	.	.	.	.	.	.	1	.	1	8
OP .002	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	2
OP .003	.	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	4
OP .005	.	.	.	2	.	.	.	.	21	.	.	.	.	.	.	.	.	.	.	1	.	.	32
OP .007	.	.	1	8	.	.	.	.	12	.	.	.	.	.	.	.	1	.	16	12	.	.	50
OP .009	.	.	1	8	.	.	.	.	15	.	.	.	.	.	.	.	.	.	4	3	4	6	41
OP .011	.	.	.	10	.	.	.	.	11	.	.	.	.	.	.	.	.	.	7	13	2	7	50
OP .013	.	2	3	15	.	.	.	.	18	.	.	.	.	.	.	.	5	.	8	13	5	1	70
OP .015	.	.	.	5	1	2	.	.	5	.	.	.	.	.	.	.	2	.	19	5	5	2	46
OP .017	.	.	.	.	3	.	.	.	4	.	.	.	.	.	.	.	.	.	.	1	.	5	13
OP .019	.	.	.	5	.	1	.	.	3	.	.	.	.	.	.	.	.	.	7	3	1	.	20
OP .021	.	.	.	1	.	.	.	.	8	.	.	.	.	.	.	.	.	.	.	1	.	.	10
OP .023	.	.	.	188	1	.	.	.	47	.	.	.	.	.	.	.	.	.	1	10	4	.	251
OP .025	.	.	.	180	.	.	.	.	21	.	.	.	.	.	.	.	.	.	.	5	.	.	206
OP .027	.	.	.	213	1	6	.	.	16	.	.	.	.	2	.	.	.	.	2	.	.	8	248
OP .029	.	.	.	113	1	4	.	.	12	.	.	.	.	10	.	.	1	.	2	1	4	20	168
OP .032	.	.	2	229	4	.	.	.	12	.	.	.	3	25	.	.	1	.	5	27	.	13	321
OP .036	.	.	.	487	1	.	.	.	19	.	.	.	.	7	.	.	.	.	.	24	.	5	543
OP .040	.	.	.	65	.	.	.	.	25	.	.	.	.	17	.	.	.	.	.	4	.	2	113
OP .044	.	.	1	43	3	.	.	.	4	.	.	.	4	42	.	.	3	.	.	.	.	.	100
OP .048	.	.	1	51	5	.	.	.	91	.	.	.	5	47	.	.	3	.	.	9	2	16	230
OP .052	.	.	2	51	.	1	.	.	27	.	.	.	.	11	.	.	.	.	.	2	1	6	101
OP .056	.	.	1	18	1	.	.	.	5	.	.	.	.	15	.	1	.	.	.	2	5	14	62
OP .060	.	.	3	11	.	.	.	.	7	.	.	.	.	18	.	.	.	.	.	2	.	2	43
OP .064	.	.	5	253	3	.	.	.	65	.	.	.	1	38	.	.	6	.	.	11	.	5	387
OP .068	.	.	4	24	5	.	.	.	24	.	.	.	5	27	1	.	14	1	1	3	2	119	
OP .072	.	.	.	16	5	.	.	.	23	.	.	.	1	47	.	.	3	.	.	1	.	13	109
OP .076	.	.	5	24	3	.	.	.	3	.	.	.	.	31	.	.	7	.	.	5	.	8	86
OP .080	.	.	5	46	1	.	.	.	32	.	.	.	1	30	.	.	7	.	.	5	.	.	127
OP .084	.	.	.	55	3	.	.	.	15	.	.	.	1	15	.	1	1	1	.	1	.	12	105
OP .088	.	.	5	26	1	.	.	.	20	.	.	.	1	5	.	.	4	.	4	2	.	2	70
OP .092	.	.	.	6	.	.	.	.	6	.	.	.	.	2	.	.	2	.	.	.	1	.	17
OP .096	.	.	3	41	2	.	.	.	5	.	.	.	.	3	.	.	2	1	.	7	.	.	64
OP .100	.	.	2	77	.	.	.	.	7	.	.	.	.	.	.	.	1	.	.	5	.	.	92
OP .104	.	.	1	20	.	.	.	.	15	.	.	.	.	14	.	.	1	.	1	7	.	1	60
OP .108	.	.	4	32	4	1	.	.	11	.	1	.	1	26	.	2	4	.	.	4	.	5	95
OP .112	.	.	.	256	.	.	1	.	39	.	.	.	3	1	.	2	2	.	3	4	.	5	320
OP .116	.	.	.	347	.	.	1	.	16	.	.	.	6	5	.	3	1	.	1	.	3	.	383
OP .120	.	.	.	97	1	.	.	.	1	.	.	.	2	3	.	2	1	.	1	1	.	1	110
OP .124	.	.	.	265	.	.	.	.	14	.	.	.	3	2	.	6	2	1	1	2	.	.	296
OP .128	.	.	.	11188	9	.	.	.	88	.	.	.	9	1	.	5	.	1	9	2	1	11	1325
OP .132	.	.	.	11300	2	.	.	.	122	.	.	.	15	1	.	2	1	4	3	.	.	3	1454
OP .136	.	.	.	338	1	.	.	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	343
OP .138	.	.	.	403	.	.	.	.	7	.	.	.	.	1	.	.	.	.	.	.	.	.	411
OP .155	.	.	.	346	.	.	.	.	18	.	.	.	.	1	.	.	.	.	.	.	.	.	372
OP .160	.	.	2	135	3	.	.	.	65	.	.	.	.	.	.	.	.	.	.	.	.	15	220
OP .162	.	.	.	206	2	.	.	.	45	.	.	.	.	2	.	.	.	.	.	.	.	.	255
OP .164	.	.	.	19	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	19
OP .166	.	.	.	2	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	1	4
OP .168	43	.	.	86	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	131

APPENDIX TABLE 7C.—Counts of selected categories of fish larvae, tabulated by station, for *Oceanographer* on zig-transect.

STATION NUMBER	<u>Bathylagus nigrigenys</u>	<u>Leuroglossus stibius urotronus</u>	<u>Cyclothone</u> spp.	<u>Ichthyococcus irregularis</u>	<u>Maurolucus muelleri</u>	<u>Vinciguerrita lucetia</u>	<u>Bathophilus</u> sp.	<u>Stomias</u> sp.	<u>Scopelarchidae</u>	<u>Trachypteridae</u>	<u>Diplospinus multistriatus</u>	<u>Lepidopus</u> sp.	<u>Nealotus tripes</u>	<u>Carangidae</u>	<u>Gobiidae</u>	<u>Labridae</u>	<u>Sciaenidae</u>	<u>Scorpaenidae</u>	<u>Serranidae</u>	<u>Bothus leopardinus</u>	<u>Citharichthys</u> spp.	<u>Syngnathus ovale</u>	<u>Symphurus</u> spp.	Total: selected categories
OP .001	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
OP .002	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
OP .003	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0
OP .005	3	.	1	.	.	8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	12
OP .007	11	.	1	.	.	18	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	30
OP .009	12	.	1	.	.	8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	21
OP .011	6	.	2	.	.	17	.	.	4	.	1	.	.	.	.	.	.	.	.	.	.	.	.	30
OP .013	20	.	3	.	.	19	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	43
OP .015	24	.	6	.	.	9	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	39
OP .017	1	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3
OP .019	8	.	1	.	.	9	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	19
OP .021	4	.	.	.	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	11
OP .023	15	.	2	.	.	51	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	69
OP .025	8	.	1	.	.	30	2	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	42
OP .027	44	67	.	.	.	110	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	225
OP .029	52	101	2	.	.	144	.	3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	302
OP .032	69	144	1	.	.	152	2	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	368
OP .036	36	451	.	.	.	120	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2535
OP .040	11	165	.	.	.	125	.	4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	306
OP .044	24	14	.	.	.	60	2	.	1	.	.	1	1	.	2	1	1	4	.	1	.	.	3	115
OP .048	93	26	1	3	54	41	3	.	.	.	.	7	.	.	3	1	1	1	1	.	1	.	2	236
OP .052	50	1	1	2	5	43	.	.	.	1	.	.	6	.	1	.	.	1	1	.	.	.	.	112
OP .056	102	6	.	1	6	13	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	130
OP .060	65	.	.	.	17	9	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	91
OP .064	94	2	2	2	6	40	2	4	.	2	.	.	1	.	.	.	.	.	.	.	.	.	.	155
OP .068	44	10	1	.	.	38	.	1	.	2	.	.	4	.	.	.	1	.	1	.	.	.	.	100
OP .072	25	5	.	.	2	3	.	.	.	.	.	.	.	.	.	.	.	1	.	1	.	.	.	37
OP .076	18	.	2	1	2	17	.	.	.	1	.	.	1	.	.	.	.	.	.	.	1	.	.	41
OP .080	49	.	1	.	.	66	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	118
OP .084	45	1	3	.	4	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	.	.	61
OP .088	34	.	6	.	.	22	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	62
OP .092	28	.	3	.	2	1	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	41
OP .096	6	.	.	2	4	1	.	1	.	.	.	.	.	.	.	.	.	2	.	6	.	.	.	16
OP .100	6	.	.	.	1	3	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	12
OP .104	2	.	.	.	7	9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	18
OP .108	31	.	1	2	19	22	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	76
OP .112	75	.	10	.	35	55	.	.	.	3	.	.	1	.	.	.	.	.	.	.	.	.	.	179
OP .116	43	.	9	2	12	100	.	.	1	2	.	.	.	.	.	.	.	.	.	.	.	.	.	169
OP .120	6	.	.	.	.	6	.	.	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	14
OP .124	4	.	.	.	.	3	.	.	1	.	.	.	1	.	.	1	.	.	.	.	.	.	.	10
OP .128	20	.	14	1	.	166	.	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	204
OP .132	15	.	12	3	.	214	.	4	1	.	.	.	.	.	.	.	.	.	.	1	.	1	.	252
OP .136	4	.	.	.	.	14	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	20
OP .138	15	.	.	.	.	9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	24
OP .155	52	.	.	.	.	37	.	.	.	.	.	.	.	.	.	.	.	1	.	1	.	.	.	92
OP .160	27	.	.	.	.	152	.	.	1	.	.	.	.	.	16	.	.	1	.	1	.	.	.	207
OP .162	6	.	3	.	.	152	.	.	1	.	.	.	.	1	18	.	.	1	1	1	.	4	3	189
OP .164	1	.	.	.	.	10	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	12
OP .166	1	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	3
OP .168	6	.	.	.	.	18	.	.	.	.	.	.	353	2	.	31	3	24	.	5	31	149	622	

APPENDIX TABLE 8.—Station data: latitude and longitude, date of collection, time of day, depth of haul, and standardized haul factor.

STATION NUMBER	Latitude	Longitude (W)	Date - Month and Day of 1967	Hour *	Depth of Haul	Standardized Haul Factor	STATION NUMBER	Latitude	Longitude (W)	Date - Month and Day of 1967	Hour *	Depth of Haul	Standardized Haul Factor
CRUISE 45							45 .165	09 17.05	111 59.0	VIII-23	1758-NT	196	3.46
45 .016	20 00.0N	118 57.2	VIII- 7	1416-D	204	3.16	45 .167	08 38.05	111 57.4	VIII-23	2346-N	211	3.80
45 .018	19 15.7N	118 56.0	VIII- 8	0127-N	214	3.41	45 .169	08 01.35	111 54.3	VIII-24	0641-D	208	3.76
45 .020	18 34.8N	118 59.0	VIII- 8	0835-D	197	3.02	45 .171	07 22.45	111 51.0	VIII-24	1211-D	208	3.00
45 .021	18 14.8N	118 58.3	VIII- 8	1216-D	212	3.54	45 .173	06 47.55	111 53.5	VIII-24	1750-NT	201	3.18
45 .023	17 41.3N	119 01.8	VIII- 8	2110-N	214	3.48	45 .175	06 01.65	111 56.7	VIII-24	2356-N	218	3.84
45 .024	17 19.9N	119 01.5	VIII- 9	0115-N	213	2.95	45 .177	05 21.15	111 59.5	VIII-25	0607-DT	197	3.33
45 .026	16 31.3N	119 02.8	VIII- 9	0904-D	175	2.51	45 .179	04 44.35	112 02.0	VIII-25	NOT QUANTITATIVE		
45 .028	16 11.3N	119 03.3	VIII- 9	1349-D	179	2.80	45 .183	04 10.05	112 05.8	VIII-25	1757-NT	195	4.20
45 .030	15 48.5N	119 05.3	VIII- 9	1830-NT	201	3.35	45 .187	03 30.05	112 01.5	VIII-25	2336-N	208	3.70
45 .032	15 10.5N	119 04.0	VIII-10	0020-N	194	3.15	45 .191	02 56.35	111 57.5	VIII-26	0611-DT	185	3.12
45 .034	14 34.2N	119 03.2	VIII-10	0636-DT	210	3.44	45 .194	02 17.95	111 59.0	VIII-27	1752-NT	208	3.44
45 .035	14 11.2N	119 03.8	VIII-10	1255-D	183	2.79	45 .198	01 30.75	111 53.1	VIII-27	2341-N	196	3.50
45 .037	13 47.3N	119 04.0	VIII-10	1755-DT	198	3.53	45 .202	00 48.65	111 46.6	VIII-28	0625-DT	181	2.86
45 .039	13 00.0N	119 03.6	VIII-10	2400-N	193	3.12	45 .206	00 17.25	111 56.5	VIII-28	1203-D	212	3.66
45 .041	12 31.0N	119 03.5	VIII-11	0534-NT	203	3.83	45 .283	00 04.2N	111 59.3	IX- 2	1321-D	174	2.49
45 .043	11 54.5N	119 02.7	VIII-11	1338-D	177	2.74	45 .287	00 32.5N	112 04.5	IX- 2	1926-N	237	4.99
45 .044	11 29.3N	119 00.5	VIII-11	1820-NT	207	3.56	45 .289	00 53.8N	112 03.3	IX- 2	0001-N	194	4.02
45 .046	10 51.7N	119 02.2	VIII-11	0005-N	216	3.78	45 .293	01 26.2N	112 01.4	IX- 3	0621-DT	202	3.81
45 .048	10 15.7N	119 03.3	VIII-12	0601-DT	177	2.67	45 .297	02 07.9N	111 58.3	IX- 3	1209-D	207	3.30
45 .050	09 34.3N	119 03.0	VIII-12	1446-D	201	3.54	45 .301	02 47.3N	112 02.0	IX- 3	1811-NT	217	3.95
45 .051	09 10.2N	118 59.5	VIII-12	2051-N	201	3.31	45 .305	03 25.8N	112 00.3	IX- 3	2335-N	209	3.60
45 .053	08 46.6N	118 58.3	VIII-13	0105-N	203	3.19	45 .309	04 08.6N	111 56.3	IX- 4	0601-DT	222	3.82
45 .054	08 28.2N	118 57.0	VIII-13	0716-D	209	3.38	45 .313	04 55.0N	111 53.5	IX- 4	1154-D	192	2.93
45 .056	07 53.2N	118 51.3	VIII-13	1505-D	203	3.28	45 .316	05 58.7N	111 57.8	IX- 4	1746-NT	215	3.53
45 .058	07 24.8N	118 47.2	VIII-13	2030-N	191	2.97	45 .319	07 01.8N	112 05.4	IX- 5	0620-DT	217	3.35
45 .060	06 50.0N	118 55.3	VIII-14	0151-N	211	3.40	45 .321	07 40.2N	112 06.8	IX- 5	1149-D	194	2.77
45 .063	05 55.5N	118 56.5	VIII-14	1053-D	209	3.46	45 .323	08 18.0N	112 01.0	IX- 5	1756-NT	194	2.58
45 .065	05 23.2N	118 51.2	VIII-14	1901-NT	224	3.90	45 .325	09 01.8N	111 54.8	IX- 5	0007-N	156	2.02
45 .067	04 53.5N	119 06.8	VIII-14	2345-N	222	3.88	45 .329	10 18.7N	111 44.0	IX- 6	1150-D	202	2.86
45 .071	04 06.0N	119 15.3	VIII-15	0730-D	219	3.61	45 .331	10 49.5N	111 39.5	IX- 6	1805-NT	175	2.45
45 .073	03 34.2N	119 14.7	VIII-15	1536-D	210	3.79	45 .333	11 27.0N	111 57.0	IX- 6	2341-N	156	2.52
45 .078	02 48.5N	119 11.0	VIII-15	0001-N	201	3.71	45 .335	12 05.7N	112 09.0	IX- 7	0605-DT	215	3.95
45 .083	02 02.0N	119 03.2	VIII-16	0640-DT	213	3.64	45 .337	12 27.8N	111 36.1	IX- 7	1146-D	207	3.17
45 .086	01 33.9N	119 02.2	VIII-16	1229-D	212	4.18	45 .339	12 58.4N	111 14.3	IX- 7	1757-VT	216	3.11
45 .090	00 57.2N	119 04.5	VIII-16	1901-NT	209	4.15	45 .341	13 33.4N	110 50.0	IX- 7	0006-N	187	3.01
45 .094	00 23.5N	119 01.5	VIII-17	0051-N	201	3.81	45 .343	13 56.3N	110 34.0	IX- 8	0805-D	193	2.79
45 .098	00 13.55	118 58.0	VIII-17	0740-D	205	3.50	45 .344	14 12.5N	110 23.0	IX- 8	1146-D	144	1.80
45 .102	00 56.35	118 51.0	VIII-17	1253-D	171	1.96	45 .346	14 38.2N	109 37.1	IX- 8	1841-N	135	1.71
45 .106	01 42.25	118 43.8	VIII-17	1901-NT	202	3.02	45 .348	14 57.4N	109 04.3	IX- 8	2345-N	199	3.16
45 .110	02 22.05	118 43.5	VIII-17	0036-N	196	4.02	45 .350	15 16.0N	108 37.5	IX- 9	0535-DT	206	3.22
45 .114	03 12.05	118 43.2	VIII-18	0800-D	212	3.26	45 .352	15 45.0N	108 08.5	IX- 9	1141-D	217	3.56
45 .117	03 38.05	118 48.5	VIII-18	1237-D	222	3.52	45 .356	16 53.0N	107 03.0	IX- 9	2334-N	186	2.87
45 .121	04 14.35	118 50.0	VIII-18	1841-NT	191	2.86	45 .358	17 20.5N	106 29.8	IX-10	0536-DT	208	3.40
45 .125	04 45.85	118 53.0	VIII-19	0243-N	216	4.20	45 .360	18 01.0N	105 41.0	IX-10	1248-D	216	3.68
45 .127	05 10.35	118 54.5	VIII-19	0745-D	192	3.31	45 .362	18 16.5N	105 20.5	IX-10	1828-N	199	3.27
45 .129	05 41.85	118 54.9	VIII-19	1231-D	215	3.91	45 .365	18 48.5N	104 44.0	IX-10	2351-N	207	3.48
45 .131	06 19.55	118 58.0	VIII-19	1831-NT	205	3.83	45 .367	19 00.0N	104 50.0	IX-13	1455-D	212	3.57
45 .133	06 57.85	119 01.5	VIII-19	2344-N	219	3.67	45 .369	19 05.3N	105 09.2	IX-13	1925-N	209	3.53
45 .135	07 26.85	119 04.0	VIII-20	0535-NT	199	3.56	45 .371	19 12.5N	105 40.5	IX-14	0024-N	203	3.33
45 .137	08 12.05	119 06.3	VIII-20	1125-D	214	3.79	45 .373	19 19.5N	106 13.8	IX-14	0601-D	221	3.63
45 .139	08 47.85	119 00.0	VIII-20	1718-DT	200	4.19	45 .375	19 34.3N	106 57.2	IX-14	1148-D	184	2.74
45 .140	09 44.75	118 59.0	VIII-21	0016-N	217	3.95	45 .377	19 36.2N	107 37.6	IX-14	1810-NT	195	3.31
45 .163	09 56.95	111 59.5	VIII-23	1153-D	217	3.82	45 .379	19 38.5N	108 24.0	IX-14	2351-N	204	3.27
							45 .381	19 41.7N	109 08.0	IX-15	0520-DT	192	2.82

APPENDIX TABLE 8.—Station data: latitude and longitude, date of collection, time of day, depth of haul, and standardized haul factor.—Continued.

STATION NUMBER	Latitude	Longitude (W)	Date—Month and Day of 1967	Hour *	Depth of Haul	Standardized Haul Factor	STATION NUMBER	Latitude	Longitude (W)	Date—Month and Day of 1967	Hour *	Depth of Haul	Standardized Haul Factor
45 .383	19 48.0N	109 56.7	IX-15	1126-D	212	3.37	46 .102	05 36.0N	097 54.0	IX- 2	2341-N	210	3.21
45 .385	19 53.0N	110 46.2	IX-15	1755-NT	200	3.07	46 .104	06 09.0N	097 45.0	IX- 3	0611-D	199	2.81
45 .387	19 58.7N	111 25.2	IX-15	2328-N	206	3.22	46 .105	06 56.4N	097 48.0	IX- 3	1211-D	213	3.45
CRUISE 46							46 .108	07 35.0N	098 00.0	IX- 3	1742-N	215	3.29
46 .002	16 14.0N	100 27.5	VIII-16	1801-NT	214	3.53	46 .110	08 25.0N	097 56.0	IX- 3	2351-N	209	3.94
46 .004	15 48.5N	100 53.8	VIII-17	0032-N	195	2.60	46 .112	08 57.5N	097 51.0	IX- 4	0411-NT	212	3.93
46 .006	15 28.0N	101 18.0	VIII-17	0730-D	209	3.31	46 .114	09 45.0N	097 48.0	IX- 4	1206-D	216	3.53
46 .007	15 13.0N	101 35.5	VIII-17	1150-D	262	3.91	46 .116	10 25.0N	098 01.0	IX- 4	1742-N	221	3.86
46 .009	14 50.5N	102 02.0	VIII-17	1750-NT	202	2.98	46 .118	11 02.5N	098 04.5	IX- 5	0011-N	204	3.08
46 .011	14 19.2N	102 38.0	VIII-17	2352-N	198	2.90	46 .120	11 28.0N	098 07.0	IX- 5	0422-NT	218	3.44
46 .013	13 56.0N	103 01.0	VIII-18	0541-D	211	3.39	46 .122	12 17.9N	097 59.0	IX- 5	1238-D	201	3.10
46 .015	13 20.0N	103 27.0	VIII-18	1141-D	211	3.34	46 .124	12 53.0N	098 03.0	IX- 5	1734-NT	220	3.68
46 .017	12 53.0N	103 56.0	VIII-18	1741-NT	214	3.51	46 .126	13 41.0N	098 03.0	IX- 6	0021-N	206	3.16
46 .019	12 16.0N	104 32.0	VIII-19	0052-N	208	2.99	46 .128	14 09.0N	098 01.0	IX- 6	0416-NT	225	3.82
46 .020	12 03.0N	104 46.0	VIII-19	0601-D	217	3.45	46 .130	14 56.0N	097 57.0	IX- 6	1211-D	199	3.11
46 .022	11 26.0N	105 04.0	VIII-19	1136-D	192	2.39	46 .132	15 38.0N	098 01.0	IX- 6	1740-NT	213	2.60
46 .024	10 46.0N	105 08.0	VIII-19	1748-NT	216	3.37	46 .134	13 12.5N	091 51.0	IX-15	1141-D	214	3.54
46 .026	10 03.5N	105 02.0	VIII-19	2351-N	195	3.10	46 .135	12 40.0N	092 03.0	IX-15	1701-NT	218	3.63
46 .028	09 31.0N	105 05.0	VIII-20	0551-D	211	3.65	46 .137	11 48.0N	092 03.0	IX-15	2340-N	206	3.31
46 .030	08 43.0N	105 03.0	VIII-20	1159-D	187	3.35	46 .139	11 08.0N	091 58.0	IX-16	0418-DT	199	2.90
46 .032	08 07.0N	105 00.0	VIII-20	1733-NT	215	3.61	46 .141	10 19.2N	091 54.0	IX-16	1151-D	204	3.23
46 .034	07 22.0N	104 57.0	VIII-20	2351-N	216	3.58	46 .143	09 42.0N	091 58.0	IX-16	1732-N	218	3.57
46 .036	06 50.0N	104 54.0	VIII-21	0551-DT	126	1.85	46 .145	08 55.0N	092 02.0	IX-16	2349-N	177	2.55
46 .038	06 13.0N	104 47.0	VIII-21	1208-D	208	3.45	46 .147	08 28.0N	092 05.0	IX-17	0419-DT	170	2.45
46 .040	05 39.0N	104 53.0	VIII-21	1749-NT	216	3.59	46 .149	07 44.0N	092 08.0	IX-17	1141-D	182	2.74
46 .042	04 52.0N	105 00.0	VIII-22	0041-N	208	3.57	46 .151	07 01.0N	092 08.0	IX-17	1731-N	204	3.19
46 .044	04 34.0N	105 02.0	VIII-22	0551-DT	214	3.56	46 .153	06 13.0N	092 03.0	IX-17	2338-N	183	2.86
46 .046	03 57.0N	105 04.0	VIII-22	1153-D	204	3.29	46 .155	05 40.0N	091 58.0	IX-18	0418-DT	224	3.88
46 .048	03 33.0N	105 11.0	VIII-22	1748-NT	213	3.58	46 .157	04 54.0N	091 52.0	IX-18	1141-D	205	3.17
46 .050	02 50.0N	105 16.0	VIII-23	0011-N	204	3.35	46 .159	04 19.0N	091 56.0	IX-18	1731-N	219	3.58
46 .052	02 28.0N	105 15.0	VIII-23	0551-DT	210	3.28	46 .161	03 34.0N	091 56.0	IX-18	2339-N	217	3.47
46 .054	01 47.0N	105 12.0	VIII-23	1227-D	157	2.05	46 .163	02 59.0N	092 00.0	IX-19	0418-DT	228	3.67
46 .055	01 29.0N	105 14.0	VIII-23	1809-N	159	2.09	46 .165	02 13.0N	092 07.0	IX-19	1141-D	195	2.64
46 .057	00 53.0N	105 19.0	VIII-23	2346-N	112	1.18	46 .167	01 39.0N	092 04.0	IX-19	1748-N	189	2.48
46 .059	00 24.0N	105 25.0	VIII-24	0606-D	84	.84	46 .169	00 54.0N	092 04.0	IX-20	0001-N	156	2.10
46 .061	00 20.0S	105 20.0	VIII-24	1159-D	161	2.36	46 .171	00 23.0N	092 04.0	IX-20	0418-DT	216	3.71
46 .063	00 42.0S	105 15.0	VIII-24	1738-NT	219	3.73	46 .173	00 14.2S	092 03.0	IX-20	1141-D	194	2.95
46 .065	01 34.0S	105 08.0	VIII-25	0001-N	194	3.09	46 .175	00 47.0S	092 03.0	IX-20	1731-N	207	3.45
46 .067	02 00.0S	105 01.0	VIII-25	0541-DT	202	3.49	46 .177	01 32.0S	092 06.0	IX-20	2339-N	197	3.33
46 .069	02 47.7S	104 48.0	VIII-25	1204-D	261	3.43	46 .179	02 03.5S	092 07.0	IX-21	0416-DT	159	2.44
46 .071	03 17.0S	104 55.0	VIII-25	1750-NT	199	3.16	46 .181	02 49.6S	092 10.0	IX-21	1141-D	128	1.57
46 .075	04 27.0S	105 00.0	VIII-28	1203-D	165	2.34	46 .183	03 27.0S	092 08.5	IX-21	1731-N	171	2.45
46 .077	05 01.0S	105 03.0	VIII-28	1750-NT	219	3.49	46 .185	04 09.5S	092 07.0	IX-21	2337-N	176	3.12
46 .079	01 04.0S	098 03.0	VIII-31	0321-N	170	2.19	46 .187	04 46.0S	092 06.0	IX-22	0418-DT	222	3.42
46 .082	00 10.9S	098 02.0	VIII-31	1218-D	196	3.06	46 .189	05 27.0S	092 05.0	IX-22	1211-D	205	3.42
46 .084	00 10.0N	098 03.0	VIII-31	1808-N	208	3.41	CRUISE 47						
46 .086	00 47.0N	098 04.0	IX- 1	0001-N	179	2.64	47 .001	05 36.0N	077 51.0	VII-31	1722-N	181	2.86
46 .088	01 12.0N	098 04.0	IX- 1	0546-D	217	3.96	47 .005	06 03.0N	078 20.0	VIII- 1	2319-N	214	3.53
46 .090	01 55.0N	098 05.0	IX- 1	1200-D	170	2.45	47 .008	06 24.0N	078 41.0	VIII- 2	0213-NT	164	2.33
46 .092	02 21.0N	098 07.0	IX- 1	1729-NT	210	3.49	47 .011	06 50.0N	079 16.0	VIII- 2	1046-D	175	2.60
46 .094	03 08.0N	098 12.0	IX- 2	0001-N	196	2.97	47 .019	06 58.0N	080 54.0	VIII- 2	2306-N	156	1.88
46 .096	03 32.5N	098 14.5	IX- 2	0531-D	198	3.12	47 .022	06 21.0N	080 41.0	VIII- 3	0331-DT	215	3.66
46 .098	04 20.0N	098 00.0	IX- 2	1208-D	198	3.14	47 .025	05 41.0N	080 32.0	VIII- 3	0943-D	203	3.10
46 .100	04 48.0N	098 04.0	IX- 2	1745-N	223	3.50	47 .028	04 51.0N	080 15.0	VIII- 3	1840-N	175	2.42

APPENDIX TABLE 8.—Station data: latitude and longitude, date of collection, time of day, depth of haul, and standardized haul factor.—Continued.

STATION NUMBER	Latitude		Longitude (W)		Date - Month and Day of 1967		Hour *	Depth of Haul	Standardized Haul Factor		STATION NUMBER	Latitude		Longitude (W)		Date - Month and Day of 1967		Hour *	Depth of Haul	Standardized Haul Factor
47 .032	04	01.0N	079	54.0	VIII- 4	0136-N	195	2.77			47 .201	01	26.0S	085	03.5	VIII-24	0249-NT	209	3.64	
47 .034	03	11.3N	079	41.0	VIII- 4	0730-D	196	2.77			47 .205	00	39.5S	085	04.0	VIII-24	0835-D	207	3.61	
47 .035	02	57.0N	079	39.0	VIII- 4	1351-D	205	3.13			47 .213	00	47.0N	084	55.0	VIII-24	2141-N	192	3.03	
47 .040	01	41.3N	079	22.0	VIII- 4	2010-N	202	2.69			47 .217	01	31.0N	084	55.0	VIII-25	0326-NT	211	3.51	
47 .049	01	00.0N	082	00.0	VIII- 5	1239-D	215	3.67			47 .221	02	08.0N	084	57.2	VIII-25	0836-D	211	3.44	
47 .053	00	18.0N	081	57.0	VIII- 5	2104-N	193	2.91			47 .225	02	47.0N	084	58.5	VIII-25	1500-DT	200	3.22	
47 .057	00	22.0S	082	00.0	VIII- 6	0211-N	210	3.38			47 .229	03	33.0N	084	54.0	VIII-25	2053-N	209	3.63	
47 .061	01	11.0S	082	02.0	VIII- 6	0748-D	193	3.09			47 .233	04	21.0N	084	49.0	VIII-26	0248-NT	207	3.26	
47 .065	01	46.0S	081	58.0	VIII- 6	1333-D	202	2.48			47 .237	05	06.5N	084	45.0	VIII-26	0835-D	213	3.76	
47 .069	02	27.0S	081	50.0	VIII- 6	2006-N	148	1.94			47 .240	05	41.0N	084	56.5	VIII-26	1336-D	205	3.51	
47 .070	03	06.0S	082	01.0	VIII- 9	2103-N	193	2.53			47 .242	06	21.0N	084	54.5	VIII-26	1957-N	146	2.10	
47 .074	03	58.0S	082	02.0	VIII-10	0305-NT	203	3.35			47 .244	06	59.0N	084	54.0	VIII-27	0156-N	207	3.58	
47 .078	04	39.0S	082	03.0	VIII-10	NOT QUANTITATIVE					47 .246	07	42.5N	085	04.0	VIII-27	0825-D	204	3.52	
47 .082	05	21.0S	082	02.5	VIII-10	1358-D	204	3.09			47 .250	08	26.5N	085	05.0	VIII-27	1430-D	210	3.61	
47 .086	06	04.0S	082	00.0	VIII-10	1941-N	208	3.06			47 .254	08	56.5N	085	01.0	VIII-27	1946-N	224	4.26	
47 .090	06	47.0S	081	58.0	VIII-11	0211-N	217	3.79			47 .258	09	26.5N	084	52.0	VIII-28	0055-N	213	3.27	
47 .094	07	28.0S	081	56.5	VIII-11	0756-D	218	3.40			47 .268	11	58.0N	088	02.0	VIII-31	0919-D	191	3.30	
47 .097	08	11.0S	082	01.0	VIII-11	1314-D	205	3.20			47 .272	11	20.8N	088	00.0	VIII-31	1441-D	195	3.10	
47 .099	08	48.0S	082	04.0	VIII-11	2111-N	214	3.39			47 .276	10	54.0N	088	10.0	VIII-31	2201-N	183	3.20	
47 .101	09	29.0S	082	05.0	VIII-12	0211-N	220	3.63			47 .278	10	21.0N	088	18.0	IX- 1	0345-DT	219	3.69	
47 .103	10	09.0S	082	09.0	VIII-12	0751-D	213	3.51			47 .280	09	44.5N	088	14.0	IX- 1	0941-D	201	3.66	
47 .105	10	02.0S	081	34.0	VIII-12	1246-D	204	3.20			47 .283	09	04.0N	088	04.0	IX- 1	1512-DT	209	3.80	
47 .107	09	50.0S	080	53.0	VIII-12	2042-N	196	2.81			47 .286	08	15.0N	087	52.0	IX- 1	2117-N	215	3.81	
47 .109	09	35.0S	080	15.0	VIII-13	0215-N	205	3.23			47 .288	07	29.0N	087	44.0	IX- 2	0330-NT	215	3.91	
47 .113	09	22.0S	079	39.0	VIII-13	0733-D	216	3.61			47 .290	06	47.0N	087	57.0	IX- 2	0949-D	207	3.32	
47 .124	12	13.0S	077	39.0	VIII-16	1340-D	200	3.05			47 .292	06	20.0N	087	57.0	IX- 2	1514-DT	207	3.48	
47 .128	12	29.0S	078	04.0	VIII-16	2216-N	200	3.00			47 .295	05	16.0N	087	57.0	IX- 2	2201-N	208	3.53	
47 .132	12	44.0S	078	52.0	VIII-17	0304-NT	213	2.50			47 .297	04	38.0N	087	57.0	IX- 3	2246-N	213	3.39	
47 .134	12	56.0S	079	28.0	VIII-17	0746-D	211	3.27			47 .301	04	00.0N	088	02.0	IX- 4	0353-DT	212	3.50	
47 .137	13	10.0S	080	13.0	VIII-17	1341-D	210	3.17			47 .304	03	22.0N	088	04.0	IX- 4	0847-D	211	3.46	
47 .139	13	27.0S	081	01.0	VIII-17	1922-N	209	3.24			47 .306	02	44.8N	087	59.0	IX- 4	1407-D	211	3.52	
47 .141	13	38.0S	081	45.0	VIII-18	0107-N	211	3.38			47 .310	02	02.0N	088	03.0	IX- 4	2027-N	204	3.32	
47 .143	13	58.0S	082	25.0	VIII-18	0719-D	213	3.53			47 .314	01	18.0N	088	06.0	IX- 5	0201-N	220	3.95	
47 .145	14	18.0S	083	05.0	VIII-18	1232-D	213	3.47			47 .318	00	33.5N	088	02.0	IX- 5	0829-D	216	3.90	
47 .147	14	33.0S	083	41.0	VIII-18	2121-N	217	3.70			47 .322	00	13.5S	088	07.0	IX- 5	1446-D	177	2.37	
47 .149	14	43.0S	084	21.0	VIII-19	0235-N	214	3.61			47 .326	00	59.0S	088	06.5	IX- 5	2053-N	150	2.01	
47 .151	14	56.0S	085	00.0	VIII-19	0806-D	216	3.75			47 .330	01	44.5S	088	08.2	IX- 6	0255-NT	185	3.10	
47 .153	14	17.0S	085	03.0	VIII-19	1259-D	210	3.53			47 .334	02	23.5S	088	02.3	IX- 6	0837-D	222	4.51	
47 .155	13	35.0S	085	00.0	VIII-19	1857-N	214	3.60			47 .338	03	04.0S	088	03.5	IX- 6	1421-D	212	4.21	
47 .157	12	44.0S	085	07.0	VIII-20	0335-NT	209	3.38			47 .342	03	47.5S	088	03.5	IX- 6	2139-N	215	4.06	
47 .159	12	06.5S	084	59.0	VIII-20	0756-D	214	3.82			47 .345	04	29.0S	087	57.0	IX- 7	0334-NT	209	3.77	
47 .162	11	30.0S	085	01.3	VIII-20	1349-D	207	3.60			47 .349	05	09.5S	088	02.0	IX- 7	0923-D	217	3.95	
47 .164	10	43.2S	085	04.0	VIII-20	2146-N	215	3.65			47 .351	05	53.0S	087	59.0	IX- 7	1513-DT	174	2.60	
47 .166	10	01.0S	085	05.3	VIII-21	0258-NT	211	3.57			47 .354	06	36.5S	087	59.0	IX- 7	2057-N	207	3.35	
47 .168	09	16.8S	085	07.3	VIII-21	0817-D	209	4.06			47 .357	07	18.0S	088	01.0	IX- 8	0207-N	205	3.32	
47 .171	08	35.0S	085	02.3	VIII-21	1325-D	212	3.61			47 .359	08	07.0S	088	03.0	IX- 8	0846-D	211	3.65	
47 .173	07	54.8S	085	06.0	VIII-21	1945-N	216	3.61			47 .362	08	55.0S	088	04.0	IX- 8	1421-D	206	3.34	
47 .175	07	16.3S	085	07.3	VIII-22	0123-N	211	3.80			47 .364	09	40.0S	088	02.0	IX- 8	2011-N	163	2.93	
47 .177	06	35.0S	085	08.5	VIII-22	0754-D	217	2.79			47 .367	10	22.0S	088	02.0	IX- 9	0207-N	209	3.23	
47 .179	05	49.7S	085	00.0	VIII-22	1301-D	221	4.39			47 .369	11	02.0S	087	58.0	IX- 9	0756-D	215	3.61	
47 .181	05	17.0S	085	01.0	VIII-22	2101-N	213	3.85			47 .371	11	48.0S	088	00.0	IX- 9	1346-D	205	3.18	
47 .185	04	28.5S	085	00.0	VIII-23	0309-NT	212	3.82			47 .373	12	31.0S	088	03.0	IX- 9	2136-N	225	4.02	
47 .189	03	51.0S	085	01.0	VIII-23	0837-D	211	3.57			47 .376	13	13.8S	088	01.0	IX-10	0311-NT	209	3.40	
47 .193	02	58.8S	085	01.0	VIII-23	1456-DT	220	4.15			47 .379	13	57.0S	087	57.0	IX-10	0902-D	211	3.69	
47 .197	02	10.0S	085	03.0	VIII-23	2055-N	222	3.97			47 .382	14	47.0S	087	59.0	IX-10	1451-DT	205	3.26	

APPENDIX TABLE 8.—Station data: latitude and longitude, date of collection, time of day, depth of haul, and standardized haul factor.—*Continued.*

STATION NUMBER	Latitude	Longitude (W)	Date - Month and Day of 1967	Hour *	Depth of Haul	Standardized Haul Factor	STATION NUMBER	Latitude	Longitude (W)	Date - Month and Day of 1967	Hour *	Depth of Haul	Standardized Haul Factor
47 .415	11 06.55	095 01.5	IX-13	0745-D	211	3.14	OP .017	10 31.05	084 54.0	XI-16	NOT QUANTITATIVE		
47 .430	09 27.05	094 59.0	IX-14	2100-N	209	3.04	OP .019	09 40.55	084 52.8	XI-16	1225-D	214	3.98
47 .432	10 14.75	095 02.0	IX-15	0253-N	229	3.41	OP .021	08 57.15	084 52.7	XI-16	1827-N	240	4.09
47 .436	08 32.05	095 01.5	IX-15	1225-D	237	4.51	OP .023	07 57.85	084 53.6	XI-16	0008-N	193	3.38
47 .438	07 39.55	095 08.5	IX-15	2040-N	214	3.80	OP .025	07 13.15	084 52.7	XI-17	0611-D	205	3.41
47 .440	06 41.05	095 09.0	IX-16	0258-N	256	4.84	OP .027	06 07.85	084 55.1	XI-17	1153-D	206	3.65
47 .443	05 55.05	095 08.3	IX-16	0908-D	249	4.26	OP .029	05 15.95	084 53.3	XI-17	1801-N	208	3.32
47 .446	05 01.55	095 05.5	IX-16	1510-D	173	2.99	OP .032	04 12.95	084 55.8	XI-17	0002-N	216	4.01
47 .450	04 14.35	095 01.0	IX-16	2036-N	216	4.54	OP .036	03 34.35	084 56.1	XI-18	0601-D	230	4.03
47 .454	03 27.35	095 00.5	IX-17	0242-N	215	4.08	OP .040	02 30.75	084 57.9	XI-18	1141-D	201	3.44
47 .458	02 40.55	095 00.5	IX-17	0817-D	161	2.31	OP .044	01 57.05	084 58.0	XI-18	1722-N	218	4.19
47 .462	01 54.35	095 04.0	IX-17	1356-D	180	2.68	OP .048	00 41.15	084 57.9	XI-18	2331-N	174	2.77
47 .466	01 01.05	095 08.5	IX-17	2101-N	210	5.19	OP .052	00 04.1N	084 57.9	XI-19	0619-D	204	3.60
47 .470	00 24.35	095 09.2	IX-18	0424-DT	166	1.98	OP .056	00 17.85	085 37.8	XI-19	1141-D	223	4.16
47 .478	01 05.2N	094 57.7	IX-19	1601-DT	205	3.43	OP .060	00 30.65	086 12.8	XI-19	1753-N	209	3.75
47 .486	02 32.5N	094 42.0	IX-19	0313-NT	205	3.00	OP .064	00 54.25	087 09.3	XI-19	2329-N	227	4.29
47 .490	03 16.3N	094 40.8	IX-19	0835-D	222	3.61	OP .068	01 10.45	087 52.2	XI-20	0532-D	216	3.78
47 .494	03 58.0N	094 59.0	IX-19	1349-D	216	3.65	OP .072	01 37.85	088 47.9	XI-20	1123-D	216	3.66
47 .498	04 44.0N	094 55.0	IX-19	2207-N	213	3.51	OP .076	01 56.85	089 26.0	XI-20	1743-N	213	3.87
47 .501	05 36.0N	094 55.5	IX-20	0319-NT	206	3.90	OP .080	02 20.75	090 24.7	XI-20	2331-N	226	3.99
47 .504	06 26.5N	094 58.5	IX-20	0853-D	219	3.39	OP .084	02 36.65	091 08.8	XI-21	0518-D	211	4.17
47 .507	07 19.0N	094 57.5	IX-20	1427-D	209	3.19	OP .088	02 59.55	092 02.8	XI-21	1056-D	216	3.00
47 .509	08 05.3N	095 02.0	IX-20	1955-N	207	2.87	OP .092	02 11.65	092 06.1	XI-21	1747-N	211	3.73
47 .511	08 56.5N	095 04.0	IX-21	0142-N	200	2.83	OP .096	01 07.55	092 03.9	XI-21	2329-N	219	3.99
47 .513	09 49.0N	095 05.0	IX-21	0722-D	193	2.44	OP .100	00 24.05	092 05.0	XI-22	0527-D	199	2.89
47 .515	10 45.5N	095 04.0	IX-21	1321-D	217	3.58	OP .104	00 46.5N	092 05.8	XI-22	1140-D	214	3.63
47 .517	11 36.0N	095 00.5	IX-21	2101-N	211	3.48	OP .108	01 24.8N	092 08.2	XI-22	1730-N	215	4.07
47 .520	12 33.2N	094 57.0	IX-22	0249-N	205	3.13	OP .112	02 35.5N	092 03.7	XI-22	2330-N	216	3.96
47 .523	13 16.0N	095 00.0	IX-22	0748-D	210	3.72	OP .116	03 15.0N	092 00.3	XI-23	0517-D	205	3.63
47 .525	14 11.0N	095 01.0	IX-22	1330-D	204	2.92	OP .120	04 23.6N	091 58.8	XI-23	1139-D	217	3.60
47 .527	15 00.3N	094 59.0	IX-22	1858-N	204	3.01	OP .124	05 08.7N	091 56.7	XI-23	1733-N	203	3.50
CROISE	OP						OP .128	06 08.4N	091 58.9	XI-23	2333-N	203	3.40
OP .001	09 17.45	079 41.9	XI-14	0228-NT	198	3.00	OP .132	06 48.3N	092 00.4	XI-24	0515-D	184	2.92
OP .002	09 41.95	080 28.4	XI-14	0836-D	255	3.88	OP .136	07 57.4N	092 02.8	XI-24	1157-D	225	4.03
OP .003	09 53.65	080 50.6	XI-14	1231-D	206	3.06	OP .138	08 12.3N	092 03.2	XI-24	1716-N	193	3.10
OP .005	10 14.05	081 26.0	XI-14	1818-N	192	3.41	OP .155	09 03.1N	092 00.4	XI-25	1153-D	216	3.78
OP .007	10 40.05	082 20.5	XI-14	0008-N	191	3.28	OP .160	10 14.9N	091 59.5	XI-25	2335-N	203	3.51
OP .009	10 58.45	082 59.4	XI-15	0626-D	191	2.63	OP .162	11 09.5N	092 00.3	XI-26	0517-D	181	3.09
OP .011	11 26.25	083 51.6	XI-15	1216-D	179	2.87	OP .164	11 43.5N	091 59.6	XI-26	1242-D	216	4.24
OP .013	11 58.15	084 54.6	XI-15	1948-N	205	2.68	OP .166	12 24.0N	092 01.1	XI-26	1713-N	204	3.40
OP .015	11 18.95	084 54.4	XI-15	0001-N	194	3.37	OP .168	13 21.2N	091 59.4	XI-26	2157-N	212	3.83

NOTES

A SECOND RECORD OF A RARE
SIPHONOPHORE *EPIBULIA RITTERIANA*
HAECKEL 1888

During a survey by the National Marine Fisheries Service research vessel *David Starr Jordan*, a siphonophore, *Epibulia ritteriana* Haeckel, of the family Epibuliidae, was collected in a neuston haul on July 10, 1971, at 0225 to 0246 hr, PST, in the northeast Pacific Ocean at lat 37°20'N, long 135°00'W. The only other record of this species was one specimen, described by Haeckel (1888), collected off Ceylon in 1882 during the *Challenger* Expedition. Evidence of the worldwide distribution is typical of most species of siphonophores.

Haeckel's identification was refuted by Totton and Bargmann (1965) who stated several reasons for their disagreement, the most important being that Haeckel had described a ring of palpons under the float which they said was a character not typical of the suborder Cystonectae. Totton and Bargmann (1965) stated further that the suborder included only the families Physalidae and Rhizophysidae; the Epibuliidae were considered "species inquirendae." They concluded that Haeckel's description was based on "an incompletely examined specimen of *Athorybia rosacea*," and "that Haeckel's figure is unrealistic and idealized though beautifully executed," and in their opinion, "if such animals existed no doubt one will be found again." They also disagreed with unillustrated descriptions of two species of Epibuliidae, one *Rhizophysa chamissomis* by Eysenhardt (1821) and the other *Epibulia erythrophysa* by Brandt (1835). It was my good fortune to collect and observe the living cystonect, described and illustrated here, which I have identified as *E. ritteriana* by reference to Haeckel's drawings and description. Haeckel's specimen is identical with mine, except that the gastrozooids in his illustration have larger and more conspicuous mouths. I have also collected specimens of *Athorybia rosacea*, identified by direct observation and comparison

with drawings by Totton and Bargmann (1965). Outstanding characters of *A. rosacea* are the shape of the pneumatophore and large and distinct bracts arranged in several layers. My specimen of *E. ritteriana* showed no evidence of bracts, nor scars or spaces where bracts could be attached. I believe, therefore, that the two species are not to be confused and that *Epibulia* does in fact exist, ergo, the family Epibuliidae.

The rarity of records for this family of cystonects may be attributed in part to the fact that as surface floating organisms they exist in a stratum seldom sampled by plankton tows because most "net time" is subsurface.

Description of *Epibulia ritteriana*

The complete corm of this Cystonectae is about 25 mm high and 20 mm in diameter, after preserved in 5% solution of formaldehyde (Figure 1). The whole colony presented brilliant shades of pink. The large ovate, almost spheric pneumatophore was coral red (light red) with the apical pore (with a sphincter) surrounded by a purple pigmentation, still visible after preservation. The crown of palpons around the float (young gastrozooids) and the siphons (gastrozooids) appeared rose, and the latter presented a purple spot near the end. Tentacles and tentilla were yellowish, the gonodendra bright red and purple.

The colony appears arranged as follows: pneumatophore and siphosome. The siphosome presents the palpons at the part closer to the pneumatophore, and the siphons at the other end, with the tentacles attached at the base; and the gonodendra distributed between the siphons.

The pneumatophore or top float is filled with gas, probably carbon monoxide as it is the case in other siphonophores (Pickwell, Barham, and Wilton, 1964). The pneumatophore is an ovate chitinous case, 8 mm × 10 mm in size. According to Haeckel (1888) the size of the pneumatophore ranged from 10 mm × 12 mm in the expanded stage to a spheroid of 3 to 4 mm after

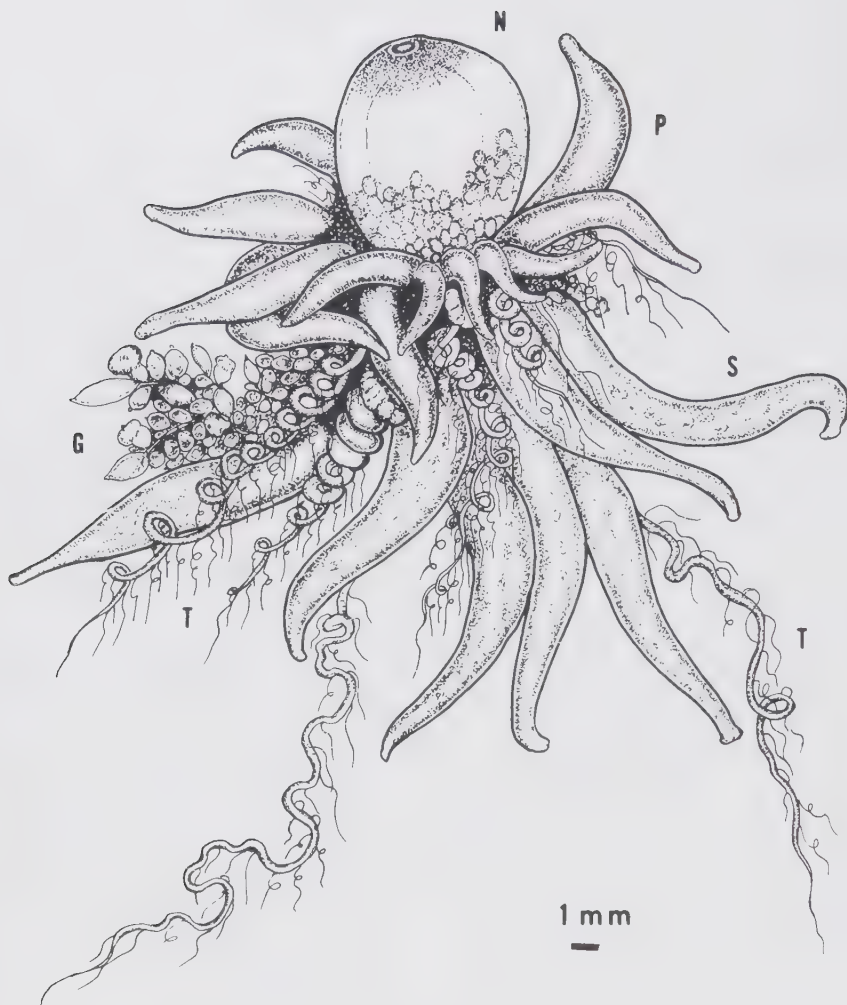


FIGURE 1.—*Epibulia ritteriana* Haeckel (1888), drawn from the specimen described in this paper. Key to the above is: N - pneumatophore, P - palpons, S - siphons or gastrozoids, T - tentacles with the tentilla, G - gonodendra.

the emission of the gas through the apical pore. The structure of the pneumatophore, according to Haeckel (1888) includes the pneumatocodon or outer wall of the pneumatophore, which is separated from the inner wall, or pneumatosac, pneumatocyst or air sac, which contains the gas gland; and the hypocystic villi (giant cells) protrude from the air sac into the pericystic space. The apical pore is closed by the stigmatis sphincter (ring muscle).

The siphosome is a short cone or ovate bladder, coiled, which Haeckel (1888) described as the "dexiotropic turning of a spire."

The palpons (feelers or testers) are slender, cylindrical tubes, smaller than the siphons, with a thick muscular wall. They connect into the vascular trunk, and the outer end is armed with cnidocysts. The palpons are consequently then both sensory and protective organs.

The siphons or gastrozooids are large feeding polyps, 15 mm to 20 mm long, rod-shaped tubes of thick muscular wall. The largest part is the stomach with the hepatic villi, and the outer opening a muscular proboscis. The opening of the mouth may be expanded in a kind of disc or sucker, divided into several lobes. Haeckel's illustrations (1888) presented the gastrozooids with extremely large and expanded mouth. A long single contractile tentacle is attached at the base of each siphon.

The tentacle arising from the base of each gastrozoid consists of a long cylindrical tube reaching to 80 mm or more than 100 mm long when fully extended. The tentacles are long, contractile, and branched along their whole length, which is covered laterally by the single branched tentilla. The tentilla are short, thin, contractile filaments. Both tentacles and tentilla are covered with nematocysts. The concave side of each tentillum has sensitive papillae, and the convex side is armed with cnidocysts. Twisted masses of tentacles and tentilla form thick bunches, difficult to disentangle.

The gonodendra are attached by a short pedicle to the periphery of the vesicular trunk, between the palpons and the siphons or gastrozooids. The gonostyle is branched, and each branch has at the end a gonopalpo and a medusoid gynophore (female gonophore) and below a bunch of roundish androphores (male gonophores) resembling altogether miniature clusters of grapes.

Epibuliidae float at the surface of the waters, using the pneumatophore, swimming mainly by the coordinated movements of the palpons, and siphons. *E. ritteriana* adopts a vertical position in the water, and the colony drifts and twists at the surface of the sea, with the pneumatophore at the top, floating at the surface, and the tentacles shortened or extended deep into the waters like fishing lines, with the gastrozooids actively searching for food.

It is possible that *Cystalia monogastrica* Haeckel (1888) may be a juvenile stage of *Epibulia ritteriana*.

The scarcity of *E. ritteriana* is probably only apparent, due to the factors previously explained. Studies on the distribution of these highly predatory animals would be of interest, when related to the distribution of some fish larvae. These Cystonectae may feed voraciously on epiplanktonic animals, mainly on those inhabiting the uppermost layers of the epiplanktonic domain (Clupeidae, Engraulidae, and other fish larvae), which would suffer heavily under this active predation.

Acknowledgments

I want to express my deep appreciation to Dr. E. H. Ahlstrom, for his advice and encouragement to prepare this work, for his interest and time devoted in reading the manuscript, and for his constructive suggestions. My appreciation is also extended to D. Kramer for his valuable editorial assistance.

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Johnston Atoll's Wake¹

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ABSTRACT

In February 1968, when the incident flow was 60 cm/sec toward the northwest, a wake resembling a von Kármán vortex street was present in the ocean downstream of Johnston Atoll (16°45'N, 169°31'W). In October 1968, when the incident flow was 15 to 20 cm/sec, no wake was detected. The February wake system moved downstream as a unit at 45 cm/sec, with a period of 4 days, a wavelength of 160 km, and a width between vortex rows of 55 km. Two-dimensional wake theory and a quantitative comparison with the strikingly similar atmospheric island wakes observed in satellite photographs suggest: that Johnston Atoll's vortex wake probably extended downstream some 600 km, or three wavelengths; that the kinetic energy was dissipated at a rate of 10^{21} ergs per eddy; and that this energy represented essentially all of the kinetic energy in the upstream flow over a width roughly twice the cross-stream diameter (26 km) of Johnston Atoll. To generate the energy dissipated by such a wake, a wind stress of 1 dyne/cm² would have to act continuously over an area of 2×10^4 km². Thus, whenever the incident flow exceeds the critical value for a vortex-wake formation, Johnston Atoll apparently dissipates wind-induced kinetic energy and disturbs the downstream flow over areas that are two orders of magnitude larger than its own area at the 100-fathom isobath. Effects of island wakes may therefore be very important within island groups and for some hundreds of kilometers downstream. However, all major island obstacles in the Pacific Ocean would dissipate less than 10% of that ocean's wind-induced kinetic energy even if all of them had vortex wakes at all times.

Introduction. A striking feature of the Pacific Ocean is the multitude of islands and island groups that dot its central and western reaches. Its islands alone would set that ocean apart from all others on this planet. How important are these island obstacles in modifying the flow of currents? Do they dissipate significant amounts of energy, thus playing in part the role often assigned to the western-boundary currents? Or are island effects confined to narrow boundary layers, with purely local importance?

The oceanographic literature has remarkably little to contribute regarding the above questions. Shtokman (1966) examined the effects to be expected, in

1. Accepted for publication and submitted to press 12 February 1972.

This work was supported in part by a grant from the U.S. Atomic Energy Commission.

theory, from island barriers that occupy various portions of a wind-driven gyre system. He did this in order to account for anomalous circulation that is often observed near islands. Uda and Ishino (1958) presented results of scale-model experiments that employed obstacles of various shapes to determine where upwelling, and consequent enrichment, might occur in the vicinity of islands. Neither Shtokman nor Uda raised the question of energy dissipation by islands.

Van Dorn, Hacker, and Lam (n.d.), who made current measurements near Swains Island and Manihiki Atoll, have suggested the presence of vortex wakes downstream of both islands, but their observations were not conclusive because of fluctuations in the incident flow and because of the short periods of observation.

No other field studies have been reported that could serve as tests of Shtokman's theoretical analysis or of Uda's scale-model experiments. In 1963, I considered accomplishing this, in part, by using historical data from the area near the Hawaiian Islands and by carrying out half a dozen cruises specifically designed to study the islands' boundary layer and wake. However, Hawaii's boundary layer and wake soon proved to be larger, more complex, and more variable than I expected; one or two ships cannot cover areas that are large enough synoptically to permit definitive analysis. Some of the eddies and countercurrents that characterize the circulation near the Hawaiian Islands may be accounted for by Shtokman's theory, others may be topographic systems of the kind discussed by Uda (Manar 1967), and still others are probably due to local horizontal wind shear generated by the venturi effect in inter-island channels (Patzert 1969).

Therefore, in 1968 I made a field study of a much simpler system: of the flow past a small isolated midocean barrier, Johnston Atoll ($16^{\circ}45'N$, $169^{\circ}31'W$). The results are presented here and are compared with island-wake phenomena on the same scale in the atmosphere.

The flow past Johnston Atoll, examined on two occasions, was timed to coincide with periods of strong and weak incident flow as reported by Kopenski and Wennekens (1966). In February and October 1968, the TOWNSEND CROMWELL and the CHARLES H. GILBERT² visited Johnston together. The CROMWELL was assigned the task of measuring large-scale flow while the GILBERT made current measurements near Johnston.

During the February cruise, a steady current, flowing northwest at about 60 cm/sec, moved past Johnston. Downstream, the flow strongly resembled a simple von Kármán vortex wake with a period of 4 days, a wavelength of 160 km, and a width between vortex rows of 55 km. This is believed to be the first von Kármán vortex wake detected in the ocean, although such wakes frequently have been observed in satellite photographs of cloud patterns (Hubert

2. Ships of the National Marine Fisheries Service, Southwest Fisheries Center, Honolulu Laboratory formerly the Bureau of Commercial Fisheries Biological Laboratory, Honolulu).

and Krueger 1962, Chopra and Hubert 1964, 1965, Lyons and Fujita 1968, and Stevenson and Nelson 1968).

Reports of von Kármán vortex wakes in the atmosphere are no longer rare, but all are due to a special combination of circumstances: the wind, an obstacle, the right kind and quantity of cloud cover at the proper level, and a satellite overhead taking pictures; all must be present. Since atmospheric vortex wakes doubtless form under much less restrictive circumstances, they are apt to be fairly common. Their discovery merely awaited the use of the proper means of observation. Similarly, von Kármán wakes, like that observed downstream of Johnston, will doubtless prove to be commonplace when we begin to look for them in the ocean.

During the October cruise, incident flow was weaker, about 15 to 20 cm/sec, and no wake could be detected near Johnston.

Previous Studies near Johnston. Aside from the results of two intensive surveys carried out by Kopenski and Wennekens (1966), little is known about the currents near Johnston. The "U.S. Coast Pilot" mentions only a 1-2-knot wave-driven current flowing south in the ship channel. The "Atlas of Surface Currents, Northwestern Pacific Ocean" (U.S. Navy, Hydrographic Office 1950) presents a few scattered observations near Johnston: the chart for February shows drift toward the west or northwest at speeds of 10 to 17 nautical miles per day within a few degrees of Johnston; comparable values (with smaller northerly components) are shown for January and March; the October chart also shows west and northwest drift, but at speeds of only 3 to 12 nautical miles per day in the vicinity of Johnston; the September and November charts show similar direction and speed. A chart published by the Deutsche Seewarte (Anonymous 1942) shows moderately persistent currents flowing westnorthwest at speeds of less than 12 nautical miles per day near Johnston.

Kopenski and Wennekens (1966) measured flow over the reefs and the nearshore areas of the central and western portions of Johnston during January-February and July-August 1965. They concluded that the dominant factors that determined the flow were: tidal currents (east-west), wave-driven flow over the reef (toward the southwest), and the North Pacific Equatorial Current, which was fairly strong and steady (toward the west) in winter, but weak and variable in summer. Their observations were made close to shore, most probably within the island's boundary layer. Their conclusions therefore apply to events within the boundary layer and not to the offshore wake, if any. Kopenski and Wennekens gave no estimate of the speed of the net incident flow. From measurements made in the seaward portions of their survey, I deduce that the net flow in winter was at least 0.2 knot (current-meter data) and may have reached a speed as high as 0.9 knot (current crosses in deep water) toward the west or slightly north of west. In summer, no net flow was apparent.

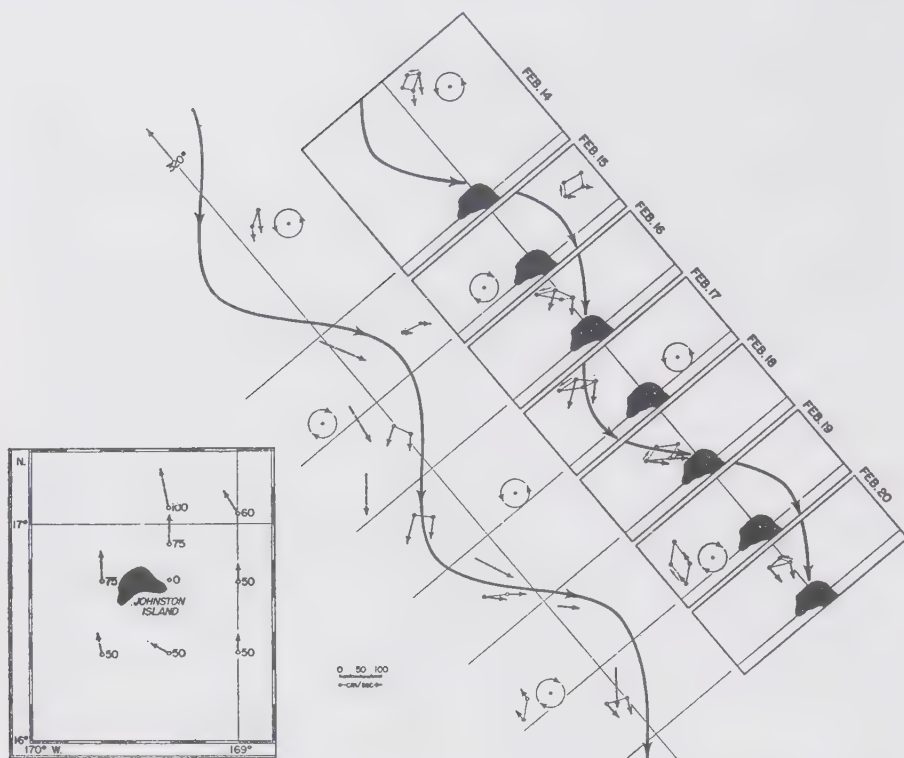


Figure 1. Currents near the sea surface off Johnston Atoll, February 1968. The individual panels in the upper right show observed longline drift during each day's fishing and the drift transformed to a frame of reference moving with the vortex wake (paired arrows). In the center, the transformed data have been arranged in sequence along a common axis. Single dashed arrows show the drift of the GILBERT as she lay to overnight. A von Kármán vortex street (sinusoidal line and circular arrows) has been fitted to the data. The inset in the lower left shows Johnston Atoll with 10- and 100-fathom depth contours and the drift (centimeters per second) of the CROMWELL during stations occupied on 12 and 13 February 1968.

Methods. In February, the CROMWELL measured the field of density for geostrophic computations, using an STD (salinity-temperature-depth recorder). At a few locations off Johnston it was possible to use radar to estimate the ships drift while on station, 12 and 13 February (Fig. 1, lower left). The GILBERT made direct measurements of near-surface currents based on the drift of longline fishing gear for one 8-hour period each day from 14 through 20 February (Fig. 1). Large drag in the water, minimal windage, and the possibility of detecting local current shear from differential motion of the two ends of the gear suggested the choice of longline as a current drogue.

In October, both ships made longline drift measurements and the CROMWELL ran a GEK (Geomagnetic Electrokinetograph) pattern (Fig. 2).

Only the longline drift data, the drifts of the two ships, and the GEK measurements provided usable information on Johnston Atoll's wake.

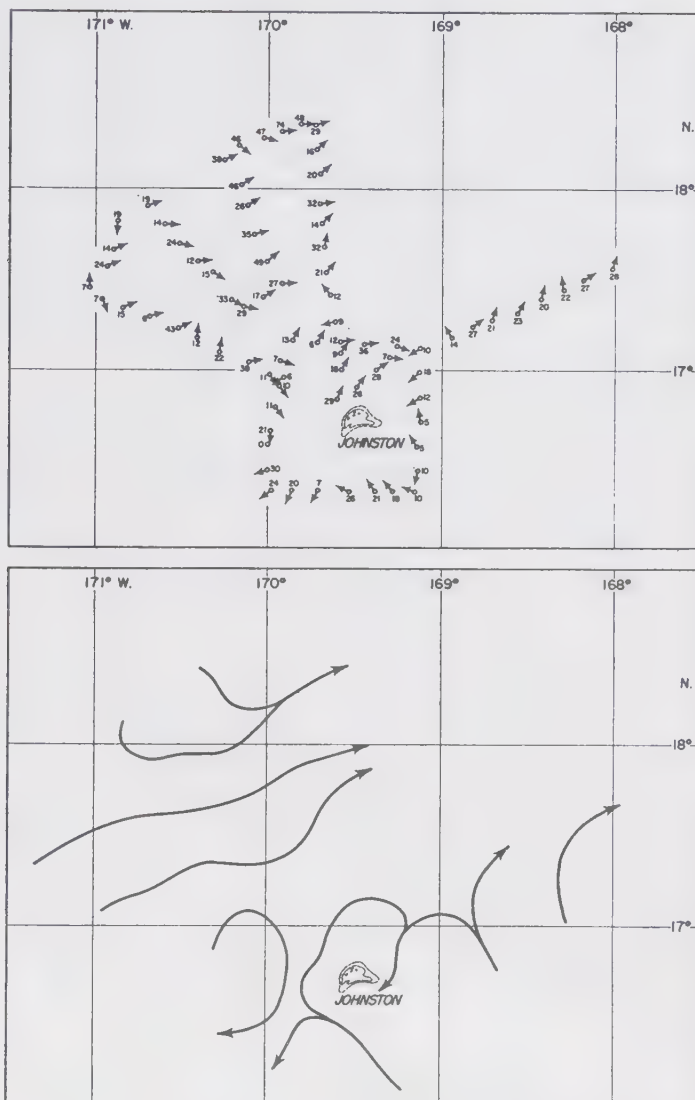


Figure 2. Surface currents off Johnston Atoll during October 1968. The upper panel shows the GEK observations, with current speeds in centimeters per second. The lower panel shows one interpretation of the GEK data—one-sided convergence with eddies marking the position of the front. Longline drift observations (not shown) agreed closely with the GEK data, but the drifts were usually too small (4 to 8 km) to be considered significant relative to the measurement errors.

For present purposes, the longline fishing gear (Yoshida 1966) is considered to be simply an 11-km length of 1-cm diameter line suspended from floats at intervals of 385 m. When set, the longline extended about 9 km from end to

end. The estimated center of drag was near the 80-m depth—the mean depth of the mainline. The maximum depth of the longline is, typically, 200 m. Since mixed-layer depths off Johnston ranged from 70 m to 100 m in February and from 60 m to 80 m in October, the longline drifted with currents in both the surface mixed layer and the upper thermocline. Velocities measured with longline gear may be regarded as averages for the upper 150 m to 200 m.

At all stations, the longline gear was set out at dawn each day and retrieved eight hours later. Positions were determined for both ends of the gear at the time of setting, twice while the gear was in the water, and again when the longline was retrieved. Successive fixes agreed to within less than 2 km when Loran A alone was used and to within less than 1 km when both Loran A and radar were used.

Results. WINDS. During February, the winds were light and variable, never exceeding 7 m/sec (15 knots). The sea was calm. The wind blew mostly from the west or northwest at 5 m/sec (10 knots) or less. As a result, the effects of the wind on the longline are considered negligible, although the ship's drift as it lay to was clearly affected by both wind and current. During the October cruise, winds were from the northeast at 7 to 10 m/sec (14 to 20 knots). Seas were moderate to somewhat rough.

CURRENTS DURING FEBRUARY. The best estimate of the incident flow is provided by the drift of the CROMWELL as she approached Johnston (from the east) on 11 February and as she left Johnston (headed northeast) on 15 February. On both occasions she experienced drift toward the northwest (315°T) at 1.2 knots (60 cm sec^{-1}) with winds of less than 10 knots from the westnorthwest. The CROMWELL also drifted northwest at 60 cm sec^{-1} on the oceanographic station most distant from Johnston (Fig. 1, lower left). In the absence of a more definitive measurement, I have therefore settled on a velocity of 60 cm sec^{-1} toward the northwest as a reasonable estimate of the incident flow.

The panels in the upper right of Fig. 1 show (to scale) the initial and final positions of the longline gear for each day and the drift during the intervening eight hours. Since the wake moved downstream, these observations were transformed to a coordinate system that moved with the wake, which (see below) traveled 45 cm/sec (0.9 knot) toward 320°T . Pairs of solid arrows show the longline drifts in this moving system of coordinates.

These transformed data are also shown in the center of Fig. 1, arranged in the proper geographic and temporal sequence along a common axis that represents the path of Johnston Atoll through the water in this system of coordinates. In addition, the GILBERT's overnight drift as she lay to is shown (single broken arrows), similarly transformed and placed in the proper location for each night. A vortex street (sinusoidal lines and circular arrows) has been subjectively fitted to the data.

Finally, the insert at the lower left shows the geographic location of John-

ston, the 10- and 100-fathom depth contours, and the drift (cm sec^{-1}) of the CROMWELL during oceanographic stations occupied on 12 and 13 February.

ANALYSIS OF FEBRUARY OBSERVATIONS. The speed and direction of the translation of the vortex wake were determined by trial and error: direction was taken to be that which yielded the best symmetry, with clockwise and counterclockwise eddies on opposite sides of the center line. Thereafter various speeds of translation were assumed; these ranged from 25 cm sec^{-1} (0.5 knot) to 75 cm sec^{-1} ; only speeds of 40 to 50 cm sec^{-1} yielded plausible results. The best fit, using 45 cm sec^{-1} , is presented in Fig. 1.

Once the speed and direction of the wake had been estimated, a more critical analysis could be performed; the results are shown in Fig. 3. The upper panel presents the longline observations, as seen by an observer who is stationary with respect to the earth's surface, together with streamlines of a theoretical von Kármán vortex wake in the same frame of reference. The second panel shows the streamlines and the observations transformed to a coordinate system that moves 45 cm/sec^{-1} toward 320°T . The third panel shows longline drifts that would have resulted (if the flow had in fact been a pure von Kármán wake) from the two-dimensional theoretical equations (Lamb 1932: 224) applied at the midpoint of each day's drift. Finally, the fourth panel shows the residuals: those vectors which, when added to the theoretical drift, yield the observed values as resultants. Residuals have not been calculated for the GILBERT's drift because her shallow draft and large superstructure make her sail appreciably even in light winds.

CURRENTS DURING OCTOBER 1968. Fig. 2 shows the GEK measurements made from the CROMWELL during October. No wake is in evidence, probably because the incident flow is too weak—roughly 15 to 20 cm/sec (0.3 to 0.4 knot). Evidently Johnston was very close to a one-sided convergence, where a northwest flow approaching the island met a current flowing at right angles, toward the northeast. I interpret the eddies just west of, and around, Johnston to be part of a line of vortices associated with the frontal zone.

Discussion. JOHNSTON ATOLL'S WAKE. The simplest way to account for the observed flow during February 1968 is to assume that it was a von Kármán vortex-street wake moving toward 320°T at 45 cm/sec , with a period of 4 days, a wavelength of 160 km, and a width between vortex rows of 55 km. Residual drift values (Fig. 3, fourth panel) make it clear that this simple kinematic model accounts for most of the data.

Agreement between the model and the observations is remarkable, considering the fact that the model assumes constant strength, direction, and speed of translation of the wake system, two-dimensional flow, and no perturbations in the incident current.

The residuals for 19 and 20 February were large relative to the navigational error and are probably significant. However, on these two days, and only then,

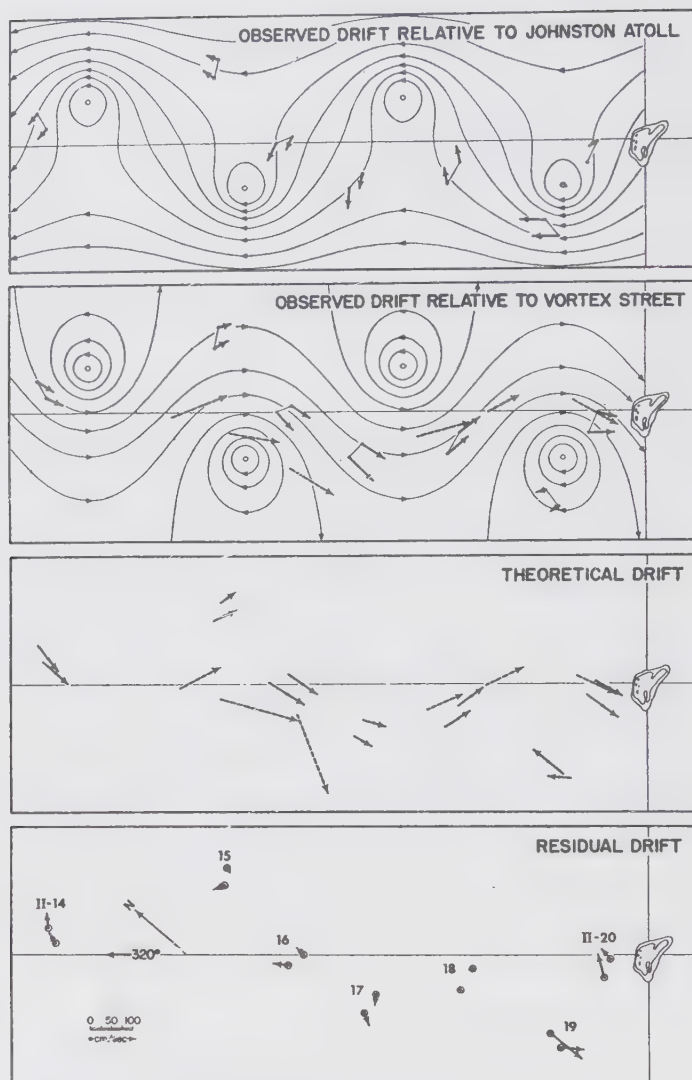


Figure 3. Analysis of February 1968 surface-current observations. Upper panel: a von Kármán vortex street moving toward 320°T , with observed longline drift data. Second panel: a stationary von Kármán vortex street fitted to the transformed longline drift data; the single broken arrows show the GILBERT's overnight drift in this same system of coordinates. Third panel: the theoretical drift at the same locations. Fourth panel: the residual drift, the difference between observed and theoretical values. Uncertainty due to navigational error is represented by small circles 4 km in diameter. Theoretical calculations are based on the values listed in Table 1.

did the longline happen to be set within less than 25 km of the center of an eddy. In the simple-point vortex model used to calculate residuals, the center

of each eddy is a singular point having infinite velocity, and theoretical velocities near the center are certainly overestimates. A more complex and realistic model, such as the Rankine vortex (Rouse 1963), which has a core in solid rotation and a zero velocity at the center, might improve agreement between theory and observation. Patzert (1969) fitted a Rankine vortex to oceanic eddies near the Hawaiian Islands, but this requires more information than was obtained from the Johnston Atoll eddies.

Currents near Johnston in October 1968 were slower than those encountered in February. The Reynolds number in February was about 70 (Table I), so in October it must have been approximately 20, based on the relative speeds of observed flow on the two occasions and assuming that the eddy viscosity remained the same. In laboratory experiments, Thom (quoted in Goldstein 1965: chapter 13) found that a circular cylinder in a wide channel developed a vortex wake at Reynolds numbers slightly above 30. It is therefore not surprising that there was no vortex wake in October.

COMPARISON WITH ATMOSPHERIC WAKES. Lyons and Fujita (1968) analyzed a number of atmospheric wakes (clear areas in the stratus) downstream of islands in the Aleutian chain; they found that wakes did not form unless the obstacle had an effective diameter that was larger than 1 km, so that the flow had an eddy viscosity Reynolds number greater than about 7. Kiska, the largest island treated by Lyons and Fujita, had the highest eddy viscosity Reynolds number, 170, and was the only island with a von Kármán vortex wake. Amchitka and Agattu, the next largest, had eddy viscosity Reynolds numbers of 128 and 133, respectively, but they did not develop von Kármán vortex wakes.

Chopra and Hubert (1964, 1965) performed a detailed analysis of atmospheric von Kármán wakes downstream of the Grand Canary, Tenerife, and Madeira islands. Their analysis of Madeira's wake is of particular interest here because it is the most detailed quantitative treatment of such wakes to date. Wilkins (1968) extended their approach by deriving equations for kinetic energy losses; he also corrected a minor error in the Chopra and Hubert analysis.

The two-dimensional kinematic theory (Lamb 1932, Prandtl and Tietjens 1934, Goldstein 1965) gives not only excellent agreement with experimental results in the laboratory but also describes major features of the islands' wakes. Table 1 presents major parameters of the wakes downstream of Madeira and Johnston, calculated from the classical theory and from Wilkins' (1968) treatment of energy dissipation. A key element in the calculation of eddy viscosity is the use of Lin's dimensionless ratio, β . Lin (1954) found that recognizable vortex-street wakes occurred only when β ($\beta = S/R$, the ratio of the Strouhal number to the Reynolds number) falls within the range 1×10^{-3} to 2.5×10^{-3} .

The calculations in Table I are based on values for distances, velocities, and

Table I. Comparison of vortex street wakes in the ocean and the atmosphere.

Variable	Symbol	Johnston Atoll	Madeira	Equations used
Effective diameter of island.....	d	26 km	40 km	-
Wavelength or pitch.....	a	160 km	190 km	-
Width between eddy rows.....	h	55 km	83 km	-
Ratio h/a	h/a	0.34	0.43	-
Speed of incident flow.....	U_o	60 cm/sec	10 m/sec	-
Speed of translation of wake.....	U_e	45 cm/sec	7.5 m/sec	-
Period of eddy pair formation.....	T	96 hours	7.2 hours	-
Period half-pendulum day.....	-	42 hours	22 hours	-
Frequency of eddy pair formation.....	N	$2.9 \times 10^{-6} \text{ sec}^{-1}$	$3.9 \times 10^{-5} \text{ sec}^{-1}$	$T = N^{-1}$
Strouhal number.....	S	0.12	0.16	$S = Nd/U_o$
Reynolds number (eddy viscosity).....	R	70	90	$R = U_o d/K$
Eddy viscosity.....	K	$2.2 \times 10^6 \text{ cm}^2/\text{sec}$	$4.4 \times 10^7 \text{ cm}^2/\text{sec}$	$K = \beta U_o^2/N^*$
Drag coefficient.....	C_d	2.1	2.1	$C_d = h/d$
Circulation strength.....	k	$6.1 \times 10^8 \text{ cm}^2/\text{sec}$	$1.1 \times 10^{10} \text{ cm}^2/\text{sec}$	$k = 2a(U_o - U_e) \coth\left(\frac{\pi h}{a}\right)$
Drag per unit height or depth (cm).....	D	$9.8 \times 10^9 \text{ g/sec}^2$	$5.0 \times 10^9 \text{ g/sec}^2$	-
Vorticity at eddy center, $t_o (= T/2)$	ζ_o	$1.3 \times 10^{-4} \text{ sec}^{-1}$	$16.6 \times 10^{-4} \text{ sec}^{-1}$	$\zeta_o = k/4\pi Kt$
Planetary vorticity, $\varphi = 16^\circ 45', 32^\circ 30'$	f	$0.42 \times 10^{-4} \text{ sec}^{-1}$	$0.78 \times 10^{-4} \text{ sec}^{-1}$	$f = 2\omega \sin \varphi$
Ratio, ζ_o/f	-	3.1	21	-
Rate of energy dissipation per unit mass ($r = 20 \text{ km}$, t_o).....	ϵ	0.007 ergs/g/sec	34 ergs/g/sec	-
Dissipation per unit volume during one eddy lifetime.....	-	4,900 ergs/cm ³	840 ergs/cm ³	-
Decay e -folding time, $r = 20 \text{ km}$	t_e	125 hours	6.3 hours	-
Age, oldest eddy.....	-	3 t_e , = 375 hours	20 hours, $\approx 3t_e$	$t_e = r^2/4K$ [from #]
Distance downstream, oldest eddy.....	-	$\sim 600 \text{ km}$, $\approx 4a$	540 km, $\approx 3a$	-

* The β referred to here is *not* d/dy , but a dimensionless ratio used by Lin (1954), which is an inherent property of the vortex street; it assumes a near-constant value (1.75×10^{-3} was used here) whenever a vortex wake is present.

$$** D = C_d \frac{\rho d U_o^2}{2} = \rho h N k = \frac{\rho k^2}{2\pi a} + \frac{\rho K h}{a} (2U_e - U_o)$$

$$\dagger \epsilon = \frac{k^2}{8\pi^2 r^2} (1 - e^{-r^2/2Kt})$$

$$\begin{aligned} \dagger\dagger \int_{t_o}^{\infty} \epsilon dt &= \frac{\rho k^2}{16\pi^2 K t_o} \left[1 + \sum_{n=1}^{\infty} \frac{\left(\frac{r^2}{n+1}\right)^n}{(n+1)!} \right] ; t_o = T/2, r = 20 \text{ km} \\ \# \zeta &= \zeta_o \exp\left(-\frac{r^2}{4Kt}\right) \end{aligned}$$

periods of Madeira's wake as reported by Chopra and Hubert and of the wake observed downstream of Johnston.

The precision of numerical values in Table I must not be overestimated. Measurements of the wake geometry and velocity are crude, and the theoretical models are highly idealized. The values for energy dissipation, in particular, are no more than order-of-magnitude estimates.

The age of the oldest eddy downstream of Madeira (see Table I) proves to be nearly three times the e -folding time for decay at a radius of 20 km. Assuming that an oceanic wake of similar size will also last approximately three times the decay e -folding time for the same radius, I obtained an age of 375 hours for the oldest Johnston Atoll eddy.

The oldest eddy in Madeira's wake was 540 km downstream. This is equivalent to three wavelengths. In the case of Johnston, an eddy 375 hours old moving downstream at 45 cm/sec should travel a distance of about 600 km, or four wavelengths.

Table I reveals striking similarities between wake systems in two different fluids. There can be little doubt that fundamentally similar phenomena are involved in both cases. The similarity is the more striking because of differences in the observations on which they are based: data for Madeira's wake were obtained from satellite photographs whereas data for Johnston's wake were obtained from a one-week series of observations of drift. These represent the two fundamental approaches used in hydrodynamics: the Eulerian, based on the field of motion at a given instant of time, and the Lagrangian, based on trajectories observed over a period of time.

Madeira has a diameter that is 50% larger than Johnston Atoll (40 km versus 26 km), and the drag coefficients are the same for both islands. Accordingly, Madeira's wake is 50% wider. The wavelengths of the two wakes differ by only 20%; if their Strouhal numbers had been equal, the wavelengths would presumably have differed also by 50%. The Strouhal number is a function of the Reynolds number and of the geometry of the obstacle (Goldstein 1965).

ENERGY DISSIPATION. The amounts of energy dissipated by Johnston Atoll's wake in February 1968 are large enough to be of some significance. If it is assumed that each eddy had an effective radius of at least 40 km and that the flow, as measured by longline, extended to some 200-m depth, then each eddy contained a volume of $2.6 \times 10^{18} \text{ cm}^3$ ($2.6 \times 10^{12} \text{ m}^3$) and dissipated a total of 1.3×10^{21} ergs during its lifetime—energy that it accumulated as it formed. Since an eddy formed every two days, the current performed work equal to at least 7.6×10^8 watts, or 1×10^6 horsepower when generating the wake.

The immediate source of this energy was the kinetic energy of incident flow, which ultimately was derived from the wind stress.

Incident flow during February 1968 moved at a speed of 60 cm/sec, so that

its kinetic energy was 1800 ergs/cm^3 as compared with the energy dissipated in the wake, 4500 ergs/cm^3 (Table I), or 10^{21} ergs for each eddy. Assuming that the incident flow extended to a depth of 100 m, the energy dissipated downstream was equivalent to that contained in a 50-km-wide cross section of the upstream flow. Since Johnston Atoll perturbed the flow over a width of some 100 km, the wake dissipated half of the energy contained in the perturbed incident flow. Similarly, the wake dissipated essentially all of the energy contained in a cross-stream width that is equal to that of the distance between vortex rows (55 km), or twice the energy incident on Johnston Atoll (26 km in width).

To compare energy dissipated in the wake with energy added by wind stress, one could use the dynamic-energy equation (Sverdrup et al. 1942: 486), but it is simpler and more direct to use the drag-per-unit depth, essentially $1 \times 10^{10} \text{ g/sec}^2$ per unit depth (Table I). If the wake eddies extended to a depth of 200 m, the total drag exerted on Johnston in February 1968 was 2×10^{14} dynes. To generate this force, a wind stress of 1 dyne/cm^2 would have to act over an area of $2 \times 10^{14} \text{ cm}^2$, or $2 \times 10^4 \text{ km}^2$. Johnston seamount has a horizontal cross-sectional area of $< 200 \text{ km}^2$ at 100 fathoms; in February 1968 its wake was dissipating energy acquired over an area that is two orders of magnitude larger. For the Pacific Ocean as a whole, with an area of $1.6 \times 10^8 \text{ km}^2$ (Sverdrup et al. 1942), 8000 vortex wakes the size of Johnston Atoll's would dissipate all of the energy introduced by wind if the mean wind stress was 1 dyne/cm^2 .

A preliminary count of midocean island obstacles in the Pacific shows that they number no more than a few hundred. Thus, even if each island had a vortex wake at all times—which Johnston Atoll, at least, does not have—less than 10% of the Pacific Ocean's wind-induced energy would be dissipated. Clearly island wakes are not a major factor in the ocean's energy balance.

Nevertheless, island wakes may have large-scale effects wherever clusters of island obstacles are spaced less than two diameters apart. In such cases, the group could dissipate virtually all incident kinetic energy whenever the eddy viscosity Reynolds number exceeds the critical value for vortex-wake formation. Examples of such island groups are the Tuamotu Archipelago, the Fiji group, the New Hebrides and Solomon islands, the Gilbert and Marshall groups, and possibly the Caroline, Mariana, and Ryukyu groups, and the high islands of Hawaii. Water probably flows freely through such island groups until some critical velocity is reached; at higher velocities, most of the flow may well be deflected entirely around the group. Such a marked qualitative change in response to a minor quantitative increase in velocity would have widespread consequences, influencing not only the potential and kinetic energy but also the distributions of physical, chemical, and biological properties within the island group and for many hundreds of kilometers downstream. For example, the dispersal of pelagic larvae spawned by coastal animals would be strongly af-

fects by the altered pattern of advection, as would sedimentation. Changes in advection would also modify the effects of air-sea heat exchange on the surface layers.

Conclusions. Evidence presented here strongly suggests that, in February 1968, Johnston Atoll had a von Kármán vortex wake. This wake had a period of 4 days, a wavelength of 160 km, and a width of 55 km between vortex rows. The Atoll's drag coefficient was 2.1, the Strouhal number 0.12.

The quantitative consequences of this hypothesis are presented in Table I, where a two-dimensional kinematic wake theory was used to estimate such parameters as the Reynolds number, eddy viscosity, circulation strength, drag-vorticity and energy dissipation, as well as the downstream duration of the wake: 600 km, or four wavelengths.

Table I also demonstrates that Johnston Atoll's vortex wake was markedly similar to the vortex wakes revealed by cloud patterns downwind of islands, as seen in satellite photographs.

In October 1968, no appreciable wake was present, presumably because the incident flow was only 15 to 20 cm/sec compared with 60 cm/sec in February; as a result the Reynolds number (based on an eddy viscosity) for October was approximately 20 compared with a value of about 70 for February.

By analogy with laboratory wake studies, one can conclude that there is a critical Reynolds number for Johnston Atoll that is greater than 20 but less than 70; here a transition occurs from a small-scale weakly turbulent wake regime to another regime in which large vortices are shed periodically, generating a von Kármán wake.

Johnston Atoll's vortex wake dissipated kinetic energy at an estimated rate of 10^{21} ergs per eddy. The energy thus dissipated was approximately equal to that contained in a 50-km-wide band of the upstream flow, or twice the cross-stream width of Johnston Atoll. To generate such energy, a wind stress of 1 dyne/cm² would have to act over an area of 2×10^4 km².

For the Pacific Ocean as a whole, energy dissipated by islands doubtless amounts to less than 10% of that generated by wind stress. However, island wakes and their influence on the distributions of properties are probably very significant in and near closely spaced island groups, such as the Marshall Islands, the Tuamotu Archipelago, and perhaps for the entire western tropical Pacific Ocean as well.

If island wakes are in fact analogous to wakes observed in the laboratory, then minor changes in the ocean-current velocity can cause major changes in the patterns of flow and in the energy dissipation near islands as the wake undergoes transition from a "laminar-flow" condition to large-scale periodic vortex shedding. It is therefore important that we learn more about island-wake phenomena, in particular: (1) determine the effects of planetary vorticity, which could influence the trajectory of the wake's eddies (Warren 1967) and

perhaps suppress formation of vortices of one sign until the local value of the vertical component of planetary vorticity is exceeded (Pohle et al. 1965), thus making the critical Reynolds number a function of latitude;³ (2) ascertain how wakes generated by groups of islands arranged in a line (Hawaiian Islands, Mariana Islands) or in clusters (Marshall Islands, Tuamotu Archipelago) differ from those generated by isolated island obstacles; and (3) determine whether the kinetic energy in the wake is carried down the spectrum of turbulence until it is lost as heat (as would be the case if the ocean were a homogenous medium) or whether appreciable amounts of kinetic energy are converted to potential energy by divergence and vertical mixing.

Finally, the presence of orderly intermediate-scale vortex wakes in the lee of islands raises a fundamental question in fluid dynamics: Why should the flow of stratified rotating fluids at Reynolds numbers of the order of 10^{10} or higher so strikingly resemble the flow of homogeneous nonrotating fluids at Reynolds numbers of the order of 10^2 ? The use of an eddy viscosity coefficient to resolve this difficulty by producing reasonable numerical values is an artifice that sheds no light on the fundamental problem: concentrated vorticity generated by the flow of a stratified rotating fluid past an internal boundary. The Rossby number is relatively high (about 0.3 for both Madeira and Johnston Atoll), so the problem is inherently nonlinear.

White (1971a, 1971b; see also McKee 1971) has dealt with barotropic flow past a circular obstacle on a β plane, which, for eastward flow, gives rise to a standing Rossby wake downstream. However, White's solution is not applicable to the Johnston Atoll or Madeira wakes, where the flow has westward components (easterly, to meteorologists). In such cases, White's "Island number", $Is = (\beta d^2/4 U_0)^{1/2}$, is imaginary (U_0 is negative) and no standing Rossby wake can form. Even if the flow were toward the east, both Johnston Atoll and Madeira are too small to generate Rossby wakes at the velocities that cause vortex-wake formation. According to White (1971a), appreciable beta effects are to be expected only when the "Island number" exceeds unity. For Johnston Atoll and Madeira, the "Island number" can be expected to have magnitudes of only 10^{-1} and 10^{-3} , respectively. White's inertial model does not account for the wakes discussed here.

Evidently vortex wakes on an intermediate scale in nature, like those observed in the laboratory, are boundary-layer phenomena involving friction as well as inertia. Theoretical work on island wakes must therefore consider not only the Rossby number ($U/\Omega L$) but also the Ekman number ($\nu/\Omega L^2$). Note that the ratio of these dimensionless numbers is the Reynolds number (UL/ν), an important parameter of wake systems both large and small. Wakes in nature probably resemble those on a much smaller scale in the laboratory

3. Observations from the Aleutian Islands by Lyons and Fujita (1968) yield a critical Reynolds number between 133 and 170 (52°N) as compared with a value between 20 and 70 for Johnston Atoll (about 17°N).

because dissipation of energy by friction is similar, in some significant sense, on both scales. Thus the island-wake problem reduces to the well-known problem of the nature of large-scale energy dissipation in turbulent fluids. Island wakes may prove to be ideal for the study of this important subject.

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SELECTIVITY OF TOWED-NET SAMPLERS

RICHARD A. BARKLEY¹

ABSTRACT

The ideal sampler for plankton and nekton is one whose selective characteristics are known to be appropriate to any given problem, so that it catches the right organisms, and rejects others, with known efficiency. This paper presents a quantitative theoretical analysis of one aspect of selectivity, avoidance of towed-net samplers. The theory is evaluated against three sets of paired samples obtained by different nets at different speeds to provide absolute and relative tests of its validity. A single sample obtained by one net towed at one speed is then analyzed to illustrate the procedure. Final evaluation of the theory awaits studies of animal behavior when confronted by a sampler, but the theory provides informative and reasonable interpretations of plankton and nekton catch data, particularly estimates of population abundance and mesh losses, even when behavior of the animals is not known.

An ideal sampler for plankton and nekton must meet at least two requirements, one qualitative and the other quantitative: It must collect or detect certain components of these extremely diverse communities, while rejecting most others; and it must do this with known effectiveness. For some purposes the qualitative aspects of sampler selectivity are relatively more important than the quantitative ones, or vice versa, but neither can ever be completely ignored in the design and selection of sampling gear.

Sampler selectivity has usually been evaluated empirically, by comparing results obtained with one sampler under different conditions or by intercomparing various sampling methods. The plankton purse seine developed by Murphy and Clutter (1972) appears to be nearly ideal for the latter purpose. It is relatively nonselective for a wide spectrum of organism types and sizes, making it useful as a "primary standard" for calibrating more selective gear, as Murphy and Clutter demonstrate.

A sound theory of sampler selectivity would be of great value as a guide to the collection and analysis of empirical data, but relatively little effort has been devoted to the development of such theory (Tranter, 1968). What I propose

to discuss here is a special, rather basic, case of selectivity: the theoretical minimum probability of certain capture, for many individual encounters between similar organisms and a towed-net sampler.

The formulation of this problem was suggested by the work of Murphy and Clutter (1972). The results resemble those obtained by Gilfillan (reported by Clutter and Anraku, 1968) but are more general. This study is an extension of my earlier theoretical work on net avoidance (Barkley, 1964) and uses the same notation.

This paper is presented in recognition of the inspiration and leadership of Oscar Elton Sette. It is appropriate that it should appear just one century after the first worldwide use of the Müller net on the *Challenger* Expedition.

METHOD

Consider a towed-net sampler moving through the water toward an individual animal (Figure 1a); for simplicity assume that the net has a circular opening of radius R and moves at a constant speed U . The animal senses the oncoming net and begins to react to it at a distance x_0 , by swimming at some mean escape speed u_e . In the time available before the net catches up, the animal either can, or cannot, get out of the way, depending on its position, speed, and di-

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rection of movement relative to the net. There is, therefore, a cone-shaped space ahead of the net which, once it encloses the animal, results in certain capture. If the animal reacts before entering the (invisible) "lethal cone," it has enough time to get out of the way of the oncoming net. The base of this "lethal cone" is the opening of the net; its apex is at a distance X ahead of the net. This distance, X , is given by the equation:

$$X = R \sqrt{\frac{U^2}{u_e^2} - 1} \quad (1)$$

which is easily obtained from the following equation (Barkley, 1964) by setting $r_0 = 0$ and $x_0 = X$:

$$u_e = \frac{U}{\sqrt{1 + \frac{x_0^2}{(R - r_0)^2}}} \quad (2)$$

Figure 1 (panels a and b) gives examples of the "lethal cone" for several values of escape speed relative to net speed. For organisms which do not react to the net ($u_e = 0$) or have very low escape speeds the "lethal cone" is very large, occupying all or almost all of the volume of water in the path of the net; the probability of capture for such organisms approaches 1.0. On the other hand, for animals whose escape speed approaches the speed of the net ($u_e \simeq U$) the "lethal cone" is short; these animals can easily dodge the oncoming net, even if they wait

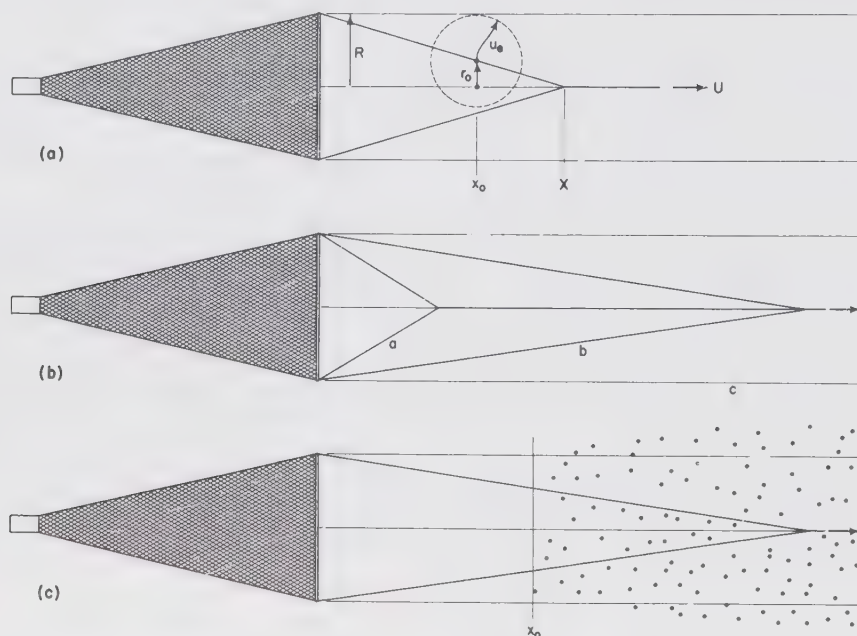


FIGURE 1.—(a) An animal at a point x_0 ahead of the net and r_0 from its axis of motion begins to react to the net. In the time available, it can go anywhere within the volume shown in dashed lines; if this volume is completely enclosed by the oncoming net, capture is certain. Animals which react before entering the cone-shaped space ahead of the net can escape; those which react after entering the "lethal cone" are caught. (b) For a given net, the length of the "lethal cone" depends only on the speed of the animal relative to the net. Cone a corresponds to animals which can move at 50% of the net's speed. Cone b represents a relative speed of 15%; cone c shows the case of no reaction. The "lethal cone" in panel a, above, corresponds to a relative speed of 30%. (c) If a school or cluster of animals reacts to the dodging movements of the animals nearest the oncoming net, only those animals already inside the "lethal cone" are certain to be captured.

until the net has almost caught up with them. We do not expect to catch any animals which can swim faster than the net; we wish to calculate minimum probabilities for certain capture, which implies that animals which could possibly escape do so. That is, the size of the "lethal cone" is minimized by assuming that animals are capable of optimum avoidance behavior.

However, probabilities of certain capture can only be calculated for animals which react individually. Animals which school or form clusters can "beat the odds" by reacting to each other's behavior instead of reacting only to the oncoming net. The effect of this is illustrated in Figure 1c, which represents a net approaching a group of animals whose reaction distances and escape velocities are assumed to be similar. If the animal shown nearest the net begins to react at the distance labeled x_0 , it can escape because it is outside of the "lethal cone." Those animals already within that cone will be captured in any case. If the other animals respond immediately to the actions of the one nearest the net, they can all escape. If, instead, they respond as individuals, as the net moves through the group, more will enter the "lethal cone" and then be captured.

Whether an organism, once captured (i.e., enclosed by the net) will be retained depends on the characteristics of the net's meshes and the size, shape, behavior, and fragility of the organism. Losses through the mesh have been reviewed by Heron, 1968; Tranter and Smith, 1968; and Vanucci, 1968. Lenarz (1972) presents results of more recent work. Losses can also occur due to faulty handling of the sampler, particularly sudden decreases in towing speed. Our primary interest here is in avoidance prior to capture, although the theory to be developed will throw some light on the problem of mesh losses.

The catch obtained from a towed-net sampler can be calculated, in principle, from equations such as the following:

$$\begin{aligned} \text{Catch} &= \text{Captures} - \text{losses} \\ &= (\text{volume sampled}) \times \left(\frac{\text{no. of organisms}}{\text{unit volume}} \right) \end{aligned}$$

$$\times (\text{probability of capture}) - (\text{losses}) \quad (2)$$

So that

$$\frac{\text{no. of organisms}}{\text{unit volume}} = \frac{(\text{catch} + \text{losses})}{(\text{volume sampled}) \times (\text{probability of capture})} \quad (3)$$

The central problem of selectivity theory is to evaluate the unknown factors in equations (2) and (3), so as to permit solution of these equations with a minimum of empirical work. The most important unknown factors are those governing probability of capture and losses after capture—primarily losses through the meshes.

Since both probability of capture and degree of mesh loss must vary widely with species, age, and condition, the above equations apply separately to each component of the plankton and nekton community.

For present purposes, a component must be defined as a set of organisms having the same probability of capture, and the same degree of mesh retention, under given circumstances. That is, they must be similar in their reaction distance, escape speed, shape, size, and condition.

The above operational definition of a component of the plankton or nekton may often coincide with the more usual biological definitions. For single species, one can reasonably expect that fish of similar size or crustaceans at the same stage of development should have similar reaction distances and escape speeds and the same percentage mesh retention. However, the distinction between the two ways of defining a component must be carefully borne in mind. The operational definition may lump several biologically defined components; to take a trivial example, bacteria, phytoplankton, and fish eggs small enough to pass through the mesh all have the same probability of capture, 1.0, and all have 0% retention. On the other hand, the operational definition may split one biological component into two or more parts; e.g., healthy and moribund animals of the same size and species should differ in their ability to avoid capture. In principle, empirical data on reaction distance,

escape speed, shape, size, and condition are needed to assign animals to different components when analyzing towed-net samples by means of the present theory. Such data could perhaps best be obtained by taking stereoscopic photographs of animals' reactions to the approach of a sampler. In practice, however, it may be possible to assign animals to operationally defined components *post facto*, based on analyses of catch data with the present theory. An example of this is to be found in Table 1, where *Bathylagus stibius* ranging from 52 to 92 mm in length were found to have essentially identical probabilities of capture and were apparently all retained by the meshes, thus meeting the criteria for a single component.

In equations (2) and (3) the major unknowns are the losses and the probability of capture. Neither can be formulated precisely until behavior of many animals, before and after entering nets of varied designs, has been studied. However, losses can be estimated to some degree from the difference between observed and theoretical catches; and probability of capture can be calculated for a limiting case, minimum probability of certain capture for individual encounters. This approach makes use of the geometry of the "lethal cone" (Figure 2). The minimum probability of capture, P_c , is:

$$P_c = \frac{\text{Area of "lethal cone" cross section at distance } x_0}{\text{Area of the sampler mouth opening}} \\ = (r/R)^2.$$

From Figure 2,

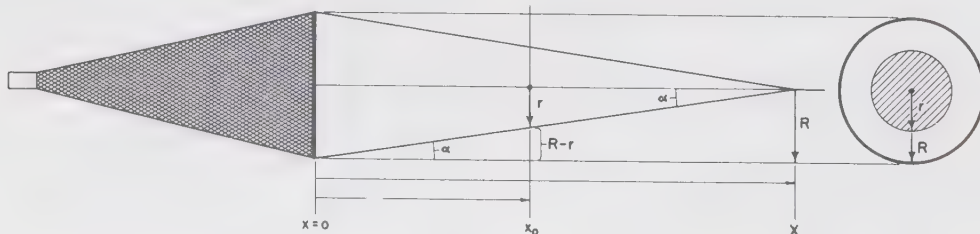


FIGURE 2.—Definition sketch for calculating P_c , the minimum probability of capture. P_c is the ratio of the area of the "lethal cone" (shaded) to the area of the net's mouth opening, at the mean reaction distance x_0 for one component of the catch.

$$\frac{R - r}{x_0} = \tan \alpha = \frac{R}{X}$$

so that

$$r = R(1 - \frac{x_0}{X})$$

and

$$P_c = (1 - \frac{x_0}{X})^2. \quad (4)$$

Substituting X from equation (1) into (4) gives

$$P_c = \left(1 - \frac{x_0}{R\sqrt{\frac{U^2}{u_e^2} - 1}}\right)^2 \quad (5)$$

which may also be written

$$P_c = \left(1 - \frac{x_0 u_e}{R\sqrt{U^2 - u_e^2}}\right)^2 \quad (6)$$

Where P_c is probability of capture, x_0 is the mean reaction distance, R is the radius of the net's opening, U is the net's speed, and u_e is the animals' mean escape speed. These results can also be derived from equations (4), (5), and (7) of my earlier analysis (Barkley, 1964).

DISCUSSION

To examine avoidance as a function of towing speed, Gilfillan (reported by Clutter and Anraku, 1968) assumed that the product $x_0 u_e$ is a constant, K . Starting with an apparent "effective"

net radius R' (identical with r in Figure 2), Gilfillan arrived at the following equation:

$$P_c = \left(1 - \frac{K}{RU}\right)^2, \quad K = x_0 u_e \quad (7)$$

where present notation has been substituted for the original and the equation slightly simplified. Clearly Gilfillan's equation is an approximate form of equation (6) for the case where u_e can be neglected compared to U ; which is to say, for animals which move much slower than the net. This approximation is good to within 5% as long as u_e is less than 30% of U .

It is not obvious that $x_0 u_e$ should in general be a constant, even for a single component of the plankton or nekton. Constancy of the product $x_0 u_e$ implies that either (1) reaction distance and escape speed individually are constant, (2) animals deficient in one of these survival traits can compensate for this by excelling in the other, or (3) animals given an unusually long time to react by faulty net design—such as a bridle or other conspicuous obstruction some distance ahead of the mouth—fail to take advantage of this warning. The first alternative is perhaps too much to expect; the second and third seem unlikely. Nevertheless, Gilfillan obtained nearly constant values for K in a series of field trials with different nets towed at various speeds, where catches of *Calanus* spp., *Euchaeta japonica*, and euphausiids were enumerated (Clutter and Anraku, 1968).

There is great practical value to knowing that K is a constant for any particular component of a sample, because this constant fully specifies the avoidance behavior of that component. If K is constant, it is possible to calculate probabilities of capture without making measurements of either x_0 or u_e , as long as U is known to exceed u_e by a factor of three or more.

Numerical values of K can be estimated, as Gilfillan suggested, from tows made at two different speeds, U_1 and U_2 , or by using two otherwise similar nets with openings of radii R_1 and R_2 , while holding other factors constant:

$$K = \frac{1 - \left(\frac{C_1}{C_2}\right)^{1/2}}{\frac{1}{R_1 U_1} - \frac{1}{R_2 U_2}} \left(\frac{C_1}{C_2}\right)^{1/2} \quad (8)$$

where C_1/C_2 is the ratio of catches of individual components in the samples taken under each of the two different conditions. Equation (8) is approximate; the exact form can be obtained

by substituting $\sqrt{U_n^2 - u_e^2}$ for U_n .

Holding "other factors" constant is obviously a problem, since the same net towed at different speeds, or different size nets towed at the same speed, may have widely different noise levels, mesh losses, hydrodynamic behavior, etc., which would tend to invalidate the comparison.

RESULTS

Although definitive tests of the theory developed above must await knowledge of avoidance and mesh escape behavior of at least some components of the plankton and nekton, a few informative comparisons can be made now between theory and catches obtained with various towed nets.

Equation (5) is presented graphically in Figure 3, where P_c , the minimum probability of capture (ordinate) is plotted as a function of the ratio u_e/U , the escape speed relative to the net's speed, for various values of the ratio x_0/R , the reaction distance relative to the net's radius. The linear graph shows the complete theoretical solution; it is used to provide a check on results obtained using the semilog format. In practice the semilogarithmic graph is more useful for analyzing catch data because it simplifies graphical calculations. Either of these graphs, as well as equations (5), (6), and (7), can of course be used to determine P_c , u_e , or x_0 if any two of these variables are known, along with R and U . For example, a 1-m net ($R = 0.5$ m) towed at 100 cm/sec should catch at least one-third ($P_c = 0.33$) of all those organisms in its path which react at a distance of 1 m and can swim 20 cm/sec ($u_e/U = 0.2$, $x_0/R = 2$).

A more interesting application is the use of Figure 3 to analyze size-frequency data from a tow, or set of tows, made with one sampler at one speed. To illustrate this application, suppose that the population in question is a species for which mesh losses are negligible beyond some

minimum size or stage of development and that the species' abundance does not change appreciably with size, or that corrections can be made for these two factors. Assume that the species' swimming ability is known, and proportional to size, while its reaction distance remains constant, or nearly constant, for all sizes sampled. Then if the catch were sorted into size class intervals (ideally, into components, in the operational sense) and counted, the size classes could each be assigned a corresponding escape speed, increasing with size; plotting these speed-frequency values as points on either graph of Figure 3 would produce a curve which resembles one of the family of curves shown on those graphs. Proper matching of observed data to the theoretical curves would yield unique values of both P_c and x_0/R (and therefore x_0 , since R is known) for each component or class interval of that species. Once P_c is known, the absolute population density can be calculated from equation (3). Finally, values of x_0 , or x_0/R , provide valuable information as to the relative merits of different sampler designs.

The following examples illustrate this use of avoidance theory. In the first example, the population density structure is known, so that P_c can be calculated directly and only x_0 remains to be determined from avoidance theory. In the second example, two different samplers are compared to obtain estimates of P_c and x_0 for both, from the theory, even though the population structure is not known. The third example illustrates information which can be obtained when one sampler is towed at two different ranges of speed. Finally, catch data from a single net, towed at one speed, are considered.

Murphy and Clutter (1972) present length-frequency data for Hawaiian anchovy, the engraulid, *Stolephorus purpurus*, caught with their plankton purse seine and a 1-m net. Their data for paired daylight tows are reproduced on Figure 4. The uppermost curve on this figure shows length-frequency data from the purse seine, assumed to represent the population structure as a function of size. I approximate these data by means of the straight line shown on this figure, in effect assuming that the population

declines exponentially as the fish grow to larger sizes. That is, $N_L = N_0 \exp(-kL)$, where N_L is the population density at length L , N_0 is a fictitious population density at zero length obtained by extrapolation, and k is a constant. The lowest curve on Figure 4, marked C_L , shows the catch (C) in each 1-mm length class (L).

To remove the effects of changes in population density, set $N_0 = 1.0$ by dividing all values of N_L by the population density at N_0 . On semi-log graph paper this can easily be accomplished simply by aligning N_0 with 1.0 on the ordinate scale, after the length-frequency values have been plotted on tracing paper using the three-cycle semilog scale of Figure 3. Next, divide each value of C_L by the corresponding value of N_L to obtain the middle curve of Figure 4, labeled C_L/N_L . This division can be performed graphically by moving each value of C_L vertically upward a distance equal to the vertical distance between N_L at the corresponding length, L , and the horizontal line $P_c = 1.0$. This procedure yields the length-frequency curve which would have been obtained if the population density in each class interval had been the same, i.e., $N_L = N_0$.

The above procedure amounts to dividing catch per unit volume by the population per unit volume, which according to equation (2) yields

$$\frac{\text{Catch/unit volume}}{\text{No. of organisms/unit volume}} =$$

Probability of capture (if losses = 0).

Thus the curve labeled C_L/N_L on Figure 4 is also a curve showing P_c for each class interval, providing that catch per unit volume has been correctly related to the population per unit volume in each class interval and that mesh losses are negligible.

Mesh losses appear to be negligible for animals larger than the two smallest class intervals, which will not be used in the analysis. Since u_e is not known, length for each class interval is converted to escape velocity by assuming that $u_e = 10L$ where u_e is in cm/sec and L is in cm. Each value thus obtained is divided by U , nominally 76 cm/sec. Resulting values of u_e/U are shown in the upper abscissa of Figure 4. The

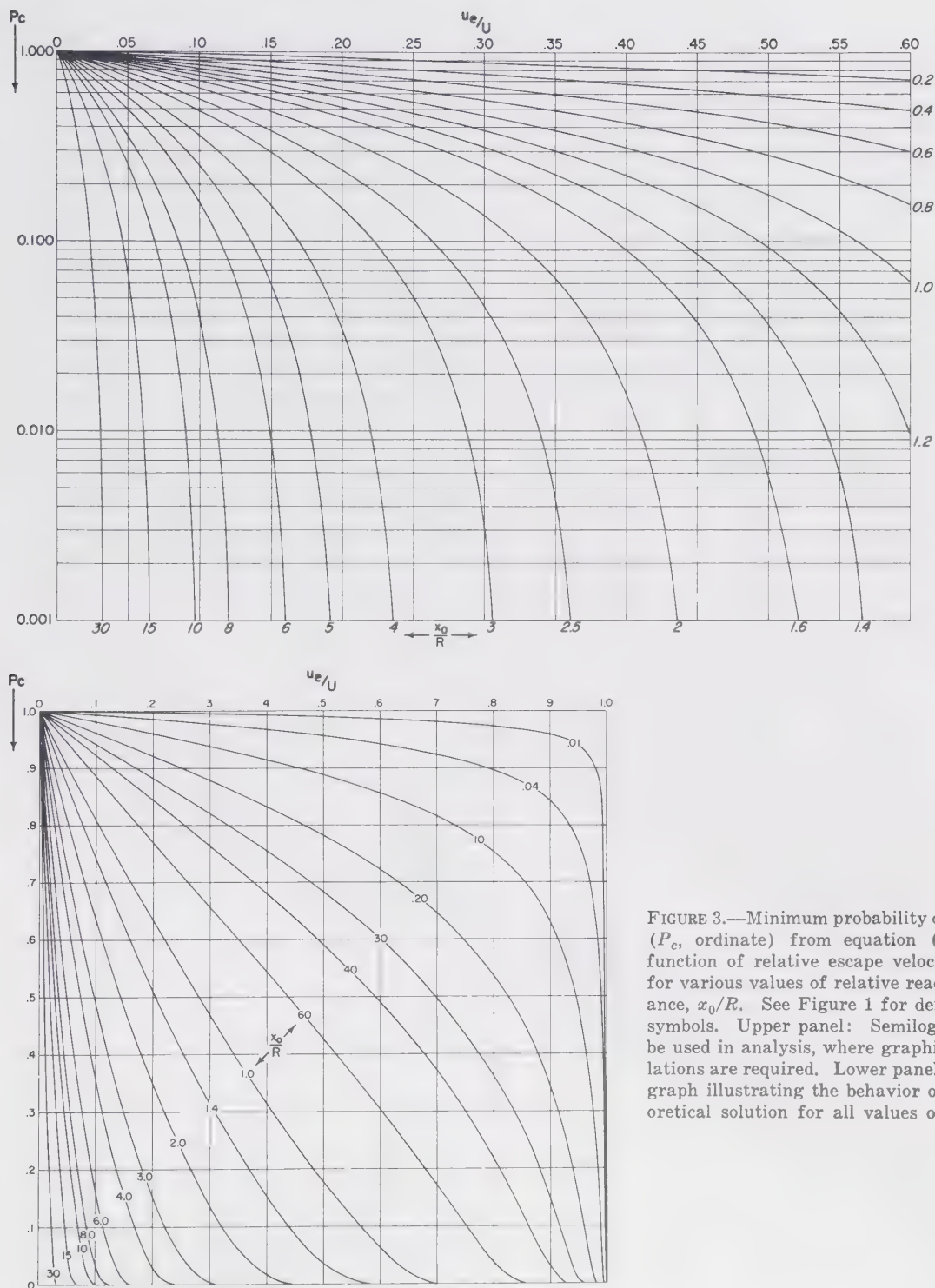


FIGURE 3.—Minimum probability of capture (P_c , ordinate) from equation (5), as a function of relative escape velocity, u_e/U , for various values of relative reaction distance, x_0/R . See Figure 1 for definition of symbols. Upper panel: Semilog graph to be used in analysis, where graphical calculations are required. Lower panel: Linear graph illustrating the behavior of the theoretical solution for all values of u_e/U .

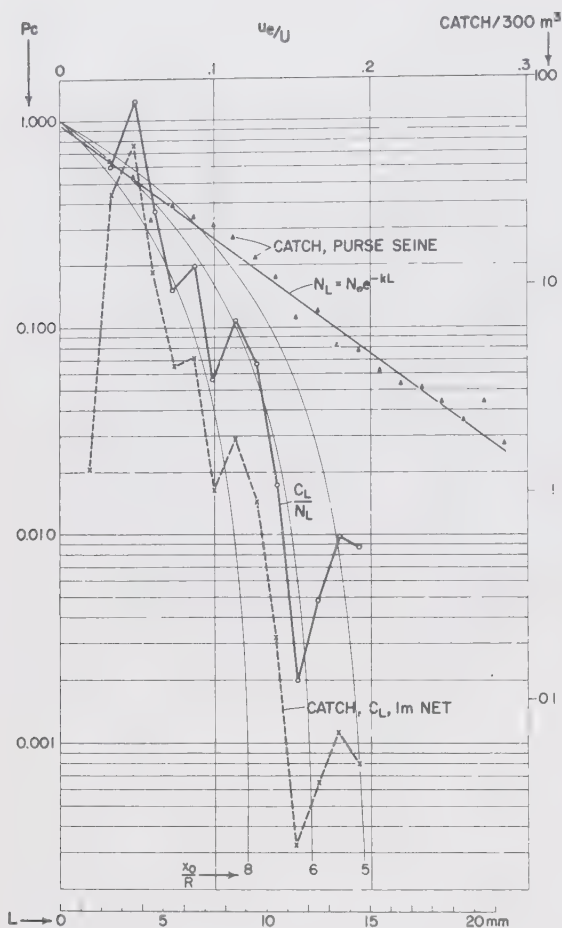


FIGURE 4.—Analysis of length-frequency data for day-light catches of *Stolephorus* from 44 paired samples. Purse seine data (triangles), a measure of absolute abundance, are approximated by the straight line, N_L . Catch with the 1-m net, C_L , has been corrected for changes in population (N) with length (L), to obtain the middle curve, C_L/N_L , which shows the minimum probability of capture, P_c , as a function of length for the 1-m net. Three theoretical curves for P_c at constant relative reaction distance (x_0/R) are reproduced from Figure 3, to show degree of fit between data and theory. Data from Murphy and Clutter (1972).

converted data can now be directly compared with the theoretical curves of Figure 3, three of which are shown on Figure 4 (the curves for P_c at $x_0/R = 5, 6$, and 8).

The adjusted 1-m net catch data fall near the theoretical curves for P_c at relative reaction

distances, x_0/R , of 6 and 8; since $R = 0.5$ m for this net, the reaction distance of *Stolephorus* apparently ranges between 3 and 4 m. Murphy and Clutter (1972) obtain comparable results from an equation they derive for calculating x_0 directly. They used similar assumptions—in particular, an escape speed of $10L$ per second—but set $P_c = 1.0$ for the third class interval (3.5 mm). Here P_c was set at 1.0 at the intercept of the purse-seine catch curve with the ordinate axis, i.e., $P_c = 1.0$ at N_0 , the fictitious population density at zero length, because only at this length does the assumed relationship between speed and length yield zero velocity. Since N_L , the population density at any given length L , is equal to N_0 for the adjusted data, the above procedure is internally consistent.

There are two exceptions to the otherwise fairly good fit between the adjusted data and the theoretical curves. The first, catch with P_c exceeding 1.0 for the third class interval (3.5 mm), may be due to sampling variability, overestimates of the water sampled by the purse seine, or underestimates of the water sampled by the 1-m net. It could also be due to less than optimum avoidance behavior by these small fish. The second exception, unexpectedly large catches in the three largest class intervals (12.5–14.5 mm) could be due to variability, or to a decrease in mean reaction distance for these animals, from a “normal” value of 3–4 m down to about 2.5 m ($x_0/R = 5$). Isaacs (1965) suggested that daytime tows should catch more than proportionate numbers of the sick, lame, or lazy; this effect should be most pronounced for the largest animals, which normally are the ones best able to dodge the net.

Minor fluctuations in the fit of the adjusted 1-m net data on Figure 4 are probably due to sampling variability, but to illustrate use of avoidance theory, suppose that the minor peaks and valleys for fish of intermediate sizes were significant. Note that these points tend to fall into two groups: those near the curve for P_c at $x_0/R = 6$, and others, $x_0/R = 8$. This could be an artifact due to schooling behavior, since group reaction should reduce the probability of capture below the theoretical minimum value for individual reaction. One measure of this effect

is an increase in the apparent reaction distance. Instead of the true value, x_0 , we would expect to obtain an apparent value which approaches ($x_0 + \text{radius of the school}$) for large schools. If *Stolephorus* schools at all sizes represented on Figure 4, the different values of x_0/R , 6 versus 8, may reflect the presence of smaller and larger schools, differing in radius by about $2R$ or 1 m.

Some support for this apparently fanciful argument can be found in the *Stolephorus* catches obtained at night by Murphy and Clutter (1972). Night purse-seine catches showed marked peaks in abundance of fish in the 7-8 mm and 11-12 mm size classes and relatively low abundances in the 4-, 9-, and 14-mm class intervals. Simultaneous tows with the 1-m net, on the other hand, yielded precisely opposite results. The 1-m net apparently undersampled abundant size classes and was more effective with the less abundant size classes. This is precisely what is expected if the purse seine catches schools of various sizes equally well, whereas the 1-m net underestimates the abundance of schooled fish, more or less in proportion to school diameter, provided only that the fish school by size and that changes in abundance are associated with changes in school size, rather than changes in the number of schools.

This detailed treatment of a single set of length-frequency data is intended only as a demonstration of the amount of information which can be extracted from such observations in the light of theory, when and if measurements of typical reaction distances and escape velocities have been made. Results of this as-yet-tentative analysis may be summarized by saying that *Stolephorus* in the 1-m net sample apparently consist of:

- A. Animals in the 1.5- and 2.5-mm class intervals, which are partially lost through the meshes and probably are unable to avoid the net.
- B. Animals 3.5 mm long, which seem to be adequately retained by the meshes and apparently are too small to effectively avoid the net.
- C. Animals 4.5 to 11.5 mm long, which react at about 3-4 m distance (proportionately more, or less, if their swimming speed is

less, or more, than 10 body lengths per second). Maximum P_c for this group is about 0.35 for the 4.5 mm fish, dropping to 0.002 for the 11.5 mm fish.

- D. Animals 12.5 to 14.5 mm long, which have anomalously large values of P_c when compared to group C, above. If these differences are significant, this implies that their reaction distances or swimming speeds, or both, may be abnormally low.

In the following examples there are no measurements of absolute abundance to compare with towed-net catch data, so assumptions will have to be made as to the relative contributions of population structure and avoidance to the outcome of sampling. Before making such assumptions it will be useful to consider the relative effects of these two factors in the case of *Stolephorus*.

On Figure 4 it can be seen that population abundance of *Stolephorus*, N_L , changed by a factor of 10 over the length interval sampled by the 1-m net. Over this same size interval the catch per class interval (C_L) changed by a factor of 1,000 or more. Thus N_L accounts for no more than 1% or 2% of the observed changes in catch length frequency, the remaining 98% to 99% being attributable to avoidance, at least for animals large enough to be fully retained by the mesh. In this strictly relative sense a 10-fold change in population density with size is in fact negligible, however important it may be in another context.

The problem of relative significance can be placed in perspective by considering whether data such as the 1-m net *Stolephorus* catches might be used to estimate population structure. Daylight 1-m net catches appear to be so overwhelmingly influenced by avoidance that even a 100-fold change in N_L might not be measurable since it could be obscured by a mere 10% error in estimating the effects of avoidance. In this sense it would be fair to assume that a population's structure is uniform, constant for all class intervals sampled by a given net if changes in N_L could not have been measured by that net. This can reasonably be taken to be true whenever the right-hand slope of the catch curves (C_L) exceeds the slope of the population curve

(N_L) by a factor of 10 or more, as it does in Figure 4.

When this assumption is made, however, it must be recognized that the results of any subsequent analysis are contaminated by whatever population structure effects are present and erroneously attributed to avoidance.

Anchovy (*Engraulis mordax*) larvae were also collected off southern California by Murphy and Clutter (1972) with a 1-m net and an Isaacs-Kidd midwater trawl (IKMT). Both nets had similar mesh size and were towed in daylight and at night at comparable speeds, nominally 75 cm/sec (although the IKMT may have been towed somewhat faster). Figure 5 shows data from these tows, converted to speed frequency by assuming that $u_e = 10L$. No estimates of absolute abundance were made for anchovy by Murphy and Clutter; the plankton purse seine was not used in these trials. However, Figure 4 shows that even 10-fold changes in N_L , abundance as a function of length, do not materially alter the shape of the *Stolephorus* speed-frequency curve. Essentially identical results could have been obtained by fitting the catch data to the theoretical curves without correction for changes in population density. Since anchovy are in many ways similar to *Stolephorus*, it may be tentatively assumed that avoidance is the major determinant of size-frequency curves for anchovy, as it clearly was for *Stolephorus* (Figure 4).

Without an independent estimate of absolute abundance, there is no priori relationship between catch and P_c . This relationship must therefore be established by seeking the best possible fit between theory and observations. Speed-frequency values were plotted on tracing paper, using the semilog coordinate system of Figure 3. The resulting graph was placed over the upper panel of Figure 3 and moved up and down until a good fit resulted (right-left motion is not allowed, since the position of points along this axis is determined by size, the size-speed relationship, and net speed). This procedure is equivalent to making various assumptions about N_0 , the fictitious population density at zero length, for which $P_c = 1$ by definition since $u_e = 0$. When this is done, the speed-frequency curves

become speed - P_c curves, showing probability of capture for each class interval. Best fits were obtained for the 1-m net anchovy catches with $N_0 = 75$ anchovy per 100 ml wet plankton (left panel, Figure 5). For the IKMT, the best fit yielded $N_0 = 60$ anchovy per 100 ml wet plankton (right panel, Figure 5). It might have been worthwhile to treat day and night catches separately, as was done for the two types of gear, but the resulting differences in N_0 between day and night tows are small, change sign for the two different nets, and probably are not significant.

Figure 5 shows that the variance for anchovy data was smaller than that for *Stolephorus* catches (Figure 4), so that the anchovy data fit the theoretical curves somewhat better. There is no way to tell whether this difference in variance is due to differences in sampling or population structure. For both nets, day-night differences in x_0/R are small, but reaction distances tend to be slightly greater for tows taken during the day, as might be expected. A surprising result is the similarity in values of x_0/R obtained for the two nets: about 6.6 for the 1-m net and 5.4 for the IKMT (if slightly lower values for the largest size classes are ignored). This yields reaction distances, x_0 , of 3.3 m for the 1-m net and 8.2 m for the IKMT. Clearly anchovy reacted to the IKMT at considerably greater distances. A light dashed line on Figure 5 (right panel) shows the dramatically increased catches which would be expected if anchovy had reacted to the IKMT at 3.3 m ($x_0/R \simeq 2$), as they apparently did in the case of the 1-m net.

The analysis shows that maximum values of P_c for the IKMT amounted to only 0.25, as compared to maximum values of P_c for the 1-m net of 0.40 or more.

Mesh retention appeared to differ for the two nets, despite similarity in mesh size (according to Murphy and Clutter, 1972, the IKMT was meshed with Nitex,² and the 1-m net with gauze silk, 56xxx grit, having openings of 0.505 and 0.55 mm, respectively). Retention dropped below 100%, based on deviations from the the-

² Reference to commercial products does not imply endorsement by the National Marine Fisheries Service.

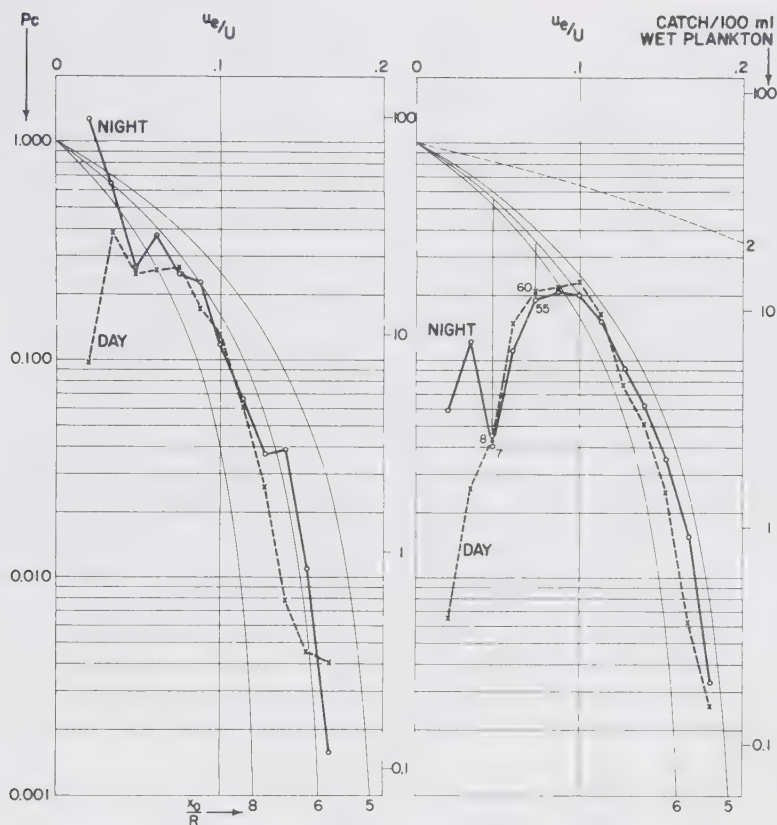


FIGURE 5.—Day and night catches of larval anchovy by a 1-m net (left) and an Isaacs-Kidd midwater trawl (right). Length-frequency data have been converted to relative escape speed (abscissa) versus frequency (ordinate, right hand scales), and compared with theoretical curves. Catch values at $P_c = 1.0$ provide estimates of abundance for all class intervals sampled. Dashed line for P_c at $x_0/R = 2$ on Isaacs-Kidd graph shows catches which could have been expected if the anchovy's reaction distance had been equal to that for the 1-m net. Net retention, based on differences between theoretical and actual catch, is shown for two class intervals on right panel: 7% to 8% for 3.75 mm fish and 55% to 60% for 5.75 mm fish. (Class sizes ranged from 1.75 mm to 12.75 and 13.75 mm by 1 mm increments.) Data from Murphy and Clutter (1972).

oretical lines of constant x_0/R , for anchovy shorter than 7.75 mm with the IKMT and 4.75 or 5.75 mm for the 1-m net. If x_0/R for a given species remains constant for any one net towed at a single speed, extrapolation of the theoretical curve toward the origin gives an indication of expected catch for smaller size classes (assuming, of course, that changes in population density

with length are negligible). This use of avoidance theory is illustrated in Figure 5, right panel, where retention is calculated at 7% to 8% for 3.75-mm fish and 55% to 60% for 5.75-mm fish. These values can be easily measured on the semilog graph; the vertical distance between the "theoretical" and the observed values is transferred to the vertical coordinate scale (e.g.,

with dividers), setting the upper point at 1.0 (100%) and reading the fraction or percentage retained at the lower point.

Let us now consider catches obtained with one type of gear at two different speeds.

Aron and Collard (1969) made carefully controlled IKMT tows at two different speed ranges, at night, using telemetering flow and depth meters to insure that the amount of water sampled was the same for all tows and that sampling was done at the desired depths. The speed of their net varied between about 1.0 and 1.7 m/sec and about 1.6 and 2.3 m/sec during the two sets of tows; I have assigned values, corresponding to modal speeds, of 1.2 and 2.0 m/sec to these tows for calculating values of u_e/U .

The assumption made thus far that $u_e = 10L$, cannot be used for the species enumerated by Aron and Collard because of their large size (up to 102 mm); escape speeds of 10 body lengths per second yield values in excess of the net's speed. Either fish that big should not have been captured, or their escape speed must be considerably less than 10 lengths per second. Accordingly, it was assumed that $u_e = 5L$ (with units of cm/sec and cm).

As was noted earlier, the effect of different choices of escape velocity to length ratios is to shift the observed points along the u_e/U axis of Figure 3, with proportional changes in resulting values of x_0/R . If a set of observed points fall precisely on the theoretical curve $x_0/R = 4$, for example, a twofold change in the assumed escape velocity results in points falling equally precisely on the curves for $x_0/R = 8$ or 2, depending on whether the escape velocities are halved or doubled. Values of P_c are not affected by the choice of velocity to length ratios.

Obviously, relative values of reaction distance, x_0 , can be estimated from the present theory, but absolute values can only be determined if in addition the animal's actual escape velocities are known, preferably as a function of size. Thus, from Figure 5 we can conclude with some assurance that anchovy react to the IKMT at distances some 2.5 times as great as they do to the 1-m net. But the reaction distances themselves, 8.3 m for the IKMT and 3.3 m for the 1-m net,

can only be correct if anchovy do in fact swim at an average speed of 10 body lengths per second when trying to avoid the net.

Of the species enumerated by Aron and Collard, *Bathylagus stilbius* seemed most amenable to analysis with avoidance theory, because the length-frequency curves for this species were somewhat smoother, and differed more with speed of tow, than was the case for other species. Figure 6 shows the speed-frequency curves for this species, assuming that $u_e = 5L$ and that $U = 120$ and 200 cm/sec, respectively. A fairly good fit could be obtained for P_c at $x_0/R \simeq 3.8$ for the faster tow and for part of the slower tow. For the fit shown in Figure 6, N_0 , the abundance at zero length, is 1,400 animals per class interval (Aron and Collard, 1969, give catches as total numbers caught during all 34 tows made in January 1966). An alternative choice of N_0 , 340 animals per class interval, produces a good fit with $x_0/R = 2.4$ for the larger animals caught by the slower tows but does not fit any of the other data. In short, there is no way to fit the length-frequency data for *B. stilbius* to the theory under the assumptions used up to now.

The assumption most likely to be violated is that population size at different lengths has negligible influence on the size-frequency curve ($N_L \simeq N_0$). This assumption when valid makes it possible to fit data from a series of length classes using a single value for N_0 , as was done for anchovy (Figure 5). If N_L varied significantly with length for *B. stilbius*, only identical length classes can be compared between the two sets of tows at different speeds. Figure 7 illustrates this procedure for the 62- and 97-mm length classes, where theoretical curves for P_c at $x_0/R = 2.8$ and 1.8, respectively, fit the data for these two size classes. Values of N_0 thus obtained were 900 individuals per class interval for 62-mm fish and 26 individuals per class interval for 97-mm fish. This 35-fold difference in apparent abundance is comparable in magnitude to differences in catch rates, 285 to 8 (48-fold) for the faster tows and 57 to 1 for the slower tows. It therefore seems likely that the shape of the length-frequency curves for *B. stilbius* was determined in large part by the population structure; avoidance apparently played

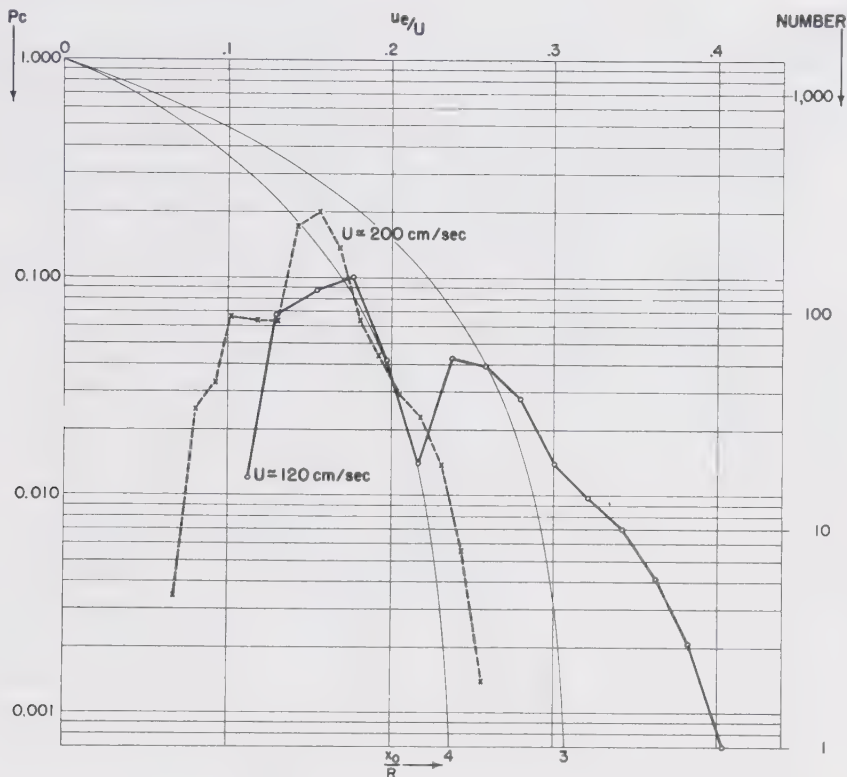


FIGURE 6.—Catches of *Bathylagus stilbius* with an Isaacs-Kidd midwater trawl at two speeds. Length frequencies converted to speed frequencies are compared with theoretical curves for P_c , showing fairly good fit at $x_0/R \approx 3.8$ for part of data. No overall fit is possible for these observations, indicating that length-frequency curves for this species were not determined primarily by avoidance. Data from Aron and Collard (1969).

a minor role, accounting only for the difference between the 35-fold range in apparent abundance and the observed 48- to 57-fold differences in catch rates for the 62- and 97-mm size classes. The most important effect of avoidance in the *B. stilbius* catch data is the nearly constant 5-fold difference in catch rates at the two different speeds, for all animals larger than 62 mm.

Figure 7 shows sample results for only two class intervals. Table 1 shows results for all class intervals of Aron and Collard's *B. stilbius* catch data: Catches (as read from length-frequency curves), ratios of catches at two speeds, and values of x_0/R , N_0 , and P_c obtained by fitting the catch data to the theoretical curves of Figure 3. Obviously, "fitting" two points to a

curve is a trivial exercise, which is only justified by the apparently consistent results obtained for larger fish in Table 1. Data from three or more sets of tows, at as many different speeds, should be used for such analyses.

Figure 7 also shows the ranges of values of u_e/U , and the extreme values for x_0/R and N_0 , which result when the full range of net speeds reported by Aron and Collard (1969) is used instead of the modal speeds. The numerical results, like the net speeds, vary by factors of about two—an indication of the uncertainty inherent not only in the *B. stilbius* data but also in the data for other species considered here, since variations in net speed comparable to those measured by Aron and Collard are doubtless present

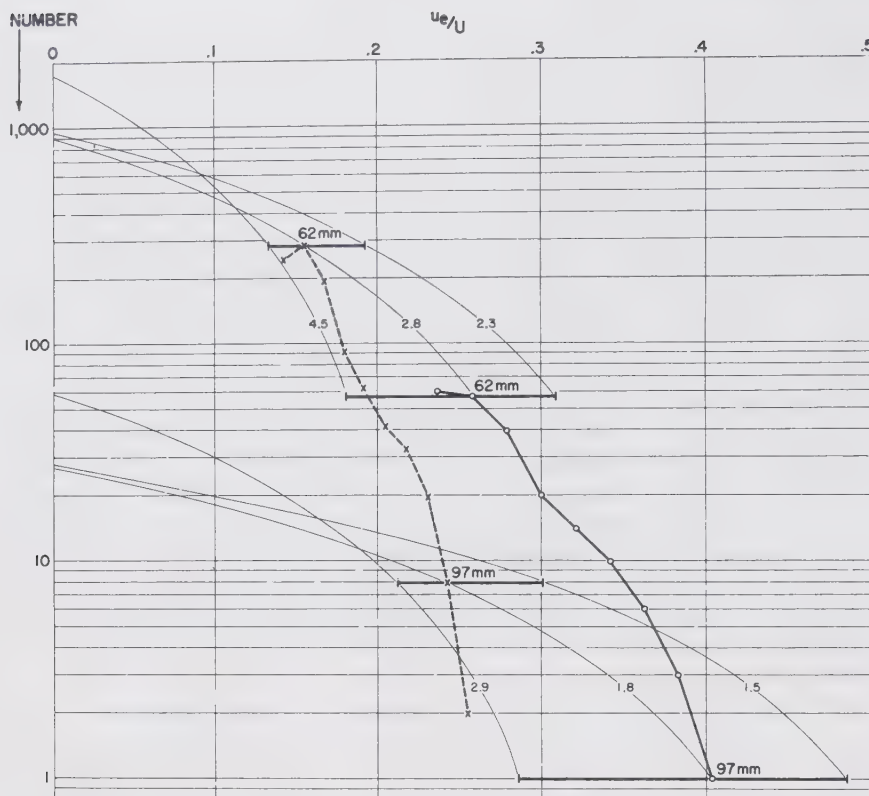


FIGURE 7.—Alternative analysis of *Bathylagus stilbius* data from Figure 6. Estimates of population (intercept of x_0/R curves for 1.8 and 2.8 with ordinate) by class interval show wide variations: from 900 animals at 62 mm to 26 animals at 97 mm. This range is comparable to the observed range in catch for these class intervals (57 to 1), showing that the length-frequency curves are primarily determined by population structure. Horizontal bars show measured ranges of towing speeds, and the effect of different speeds on the analysis. Data from Aron and Collard (1969).

during any normal towing procedure. This uncertainty does not affect the qualitative conclusions obtained from theoretical analyses; it is quite clear, for example, that anchovy react earlier to the IKMT than they do to the 1-m net. It is also quite clear that the population structure of *B. stilbius* determines the shape of the catch size-frequency curve, whereas differences in overall levels of catch for this species at two ranges of towing speed are due to avoidance, at least for those animals effectively retained by the meshes. In any case, numerical estimates of parameters such as P_c and population density which are correct to within a factor of two or

less are entirely adequate for many purposes.

Simultaneous solutions for P_c as a function of length have been obtained from the theoretical equations for three pairs of samples from as many populations. The results, while not definitive, appear encouraging.

It should therefore be possible to apply the theory to a more typical set of data, a single composite sample of larval and juvenile stages of *Katsuwonus pelamis*, the skipjack tuna. These animals were sampled with a large midwater trawl, the Cobb pelagic trawl (Higgins, 1970), during a series of five equatorial cruises made by the RV *Townsend Cromwell* in 1969-70. Repli-

TABLE 1.—Analysis of catches of *Bathylagus stilbius* with an Isaacs-Kidd midwater trawl towed at two speeds, based on avoidance theory as illustrated in Figure 7. Data from Aron and Collard (1969).

Standard length (mm)	Catches		Catch ratio	Relative reaction distance x_0/R	Population abundance number per class interval	Probability of capture		Notes
	Low speed	High speed	High speed					
			Low speed					
27	17	5	0.29	--	--	--	--	1
32	93	36	0.39	--	--	--	--	1
37	127	46	0.36	--	--	--	--	1
42	143	94	0.65	--	--	--	--	1
47	60	90	1.5	1.8	150	0.41	0.61	2
52	20	90	4.5	3.3	300	0.068	0.31	2
57	61	248	4.1	2.9	720	0.085	0.34	2
62	57	285	5.0	2.8	900	0.063	0.31	--
67	40	195	4.9	2.6	660	0.061	0.31	--
72	20	92	4.6	2.3	280	0.073	0.33	--
77	14	63	4.5	2.1	200	0.071	0.32	--
82	10	42	4.2	1.9	120	0.084	0.25	--
87	6	33	5.5	1.9	100	0.060	0.33	2
92	3	20	6.7	1.9	62	0.050	0.33	2
97	1	8	8.0	1.8	26	0.036	0.29	2
102	0	2	--	--	--	--	--	--

¹ Mesh losses probably significant, analysis with avoidance theory inappropriate.

² Mesh losses may be significant, analysis with avoidance theory questionable.

³ Sample size inadequate, results of analysis may be seriously in error.

cate 6-hr tows were taken every night for (usually) five successive nights at each of five locations (lat 12°N, 7.5°N, 3.5°N, 0°, and 3.5°S at long 145°W) during these cruises. Catches of skipjack larvae and juveniles during each of these cruises are summarized in Table 2.

Length-frequency data from three cruises, numbers 43, 44, and 48, were kindly made available to me by Walter M. Matsumoto. These data were similar for all three cruises and were therefore pooled to obtain a smoother curve (Figure 8, right panel). Of the 510 animals in this sample, 6 could not be measured. Another 5, the largest (see Figure 8, right panel) were suspected of being atypical, possibly moribund and unable to properly avoid the trawl. Figure 8 (left panel) shows the data for the remaining animals, converted to speed frequency using $u_e = 10L$ and $U = 150$ cm/sec.

Since the skipjack population structure as a function of length, N_L , is completely unknown, two extreme assumptions are considered: First, that avoidance has no effect, so that virtually all of the drop in catch with increasing length (Figure 8) is due to changes in the population. Second, that population structure has no effect, so that the length-frequency curve is determined only by avoidance and mesh losses.

The first assumption is illustrated in Figure 9, left panel, where the lowest curve shows speed-

frequency values. The straight line represents N_L , assuming the largest possible exponential decrease in population with size, consistent with the catch data. The upper curve shows P_c , obtained by dividing the catch data by N_L after setting $N_0 = 1.0$, exactly as was done on Figure 4. This analysis results in a wide range of values for P_c and x_0/R . N_0 in this case becomes 100%, equivalent to 500 individuals per class interval. Figure 9, right panel, shows P_c plotted on the linear theoretical graph of Figure 3.

The alternative extreme, assuming that $N_L = N_0$ so that population has no influence on catch length frequencies, is illustrated in Figure 10. There is no single apparent "best fit," between observation and theory, so three alternatives are considered. The upper curves, marked A, show

TABLE 2.—Skipjack larvae and juveniles caught with the Cobb pelagic trawl during RV *Townsend Cromwell* equatorial cruise series. Samples were taken along long 145°W, at lat 12°N, 7.5°N, 3.5°N, 0°, and 3.5°S.

Cruise no.	Dates	Number of tows	Number of successful tows	Skipjack caught
43	May 7- June 2, 1969	24	16	197
44	July 6- Aug. 3, 1969	25	10	154
46	Oct. 14- Nov. 13, 1969	27	11	297
47	Jan. 20- Feb. 25, 1970	21	1	1
48	Mar. 30- Apr. 30, 1970	25	15	158

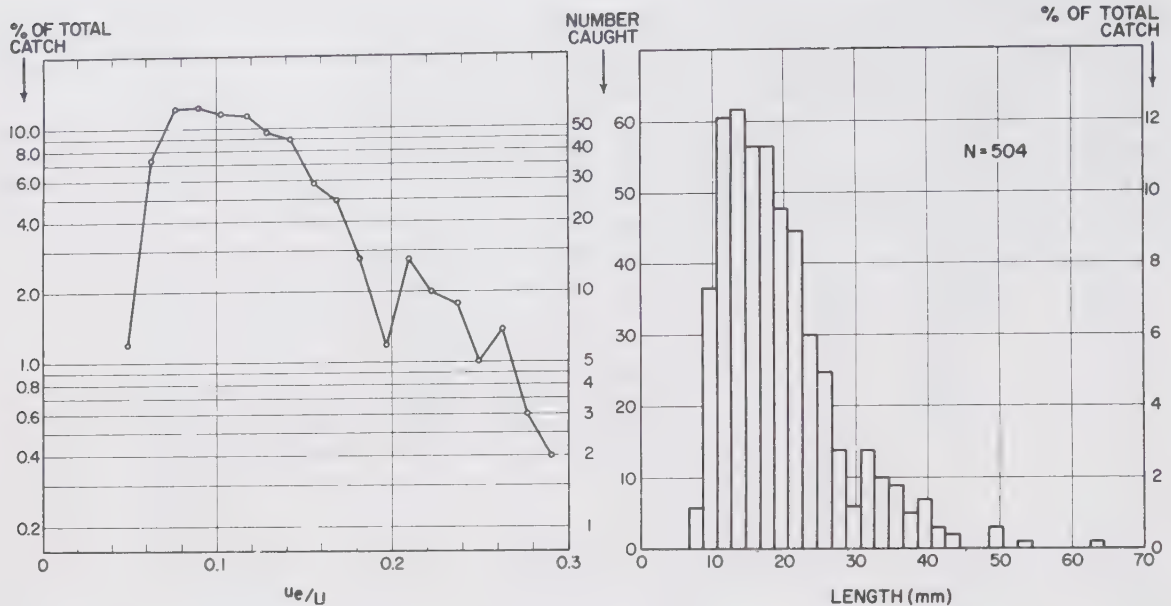


FIGURE 8.—Speed-frequency curve for skipjack larvae caught by a Cobb pelagic trawl (left panel) obtained from a length-frequency curve (right panel). Data courtesy of W. M. Matsumoto, NMFS, Southwest Fisheries Center, Honolulu Laboratory.

the data aligned to yield a fit for the best sampled class intervals. The lower curve, C, is aligned so as to fit the theoretical curves in regions of maximum slope, where sampling is most sensitive to avoidance. The middle curve, B, is a compromise which yields a reasonable fit at intermediate class intervals. Although all three analyses look plausible in the left panel of Figure 10, the linear graph shown on the right of Figure 10 clearly demonstrates that curve B yields the best match between theory and observation.

In principle there is no reason to prefer the analyses shown on Figure 10 to their alternative, Figure 9. However, I personally regard curve B on Figure 10 as the best solution because it provides the simplest and most informative explanation for the observations.

Note that all three sets of curves on Figure 10 fit two separate theoretical curves, in two distinct and well-separated groups of class intervals. As in previous examples, P_c for the largest animals markedly exceeds the values which would be expected if the theoretical x_0/R curve for smaller animals were simply extrapolated toward the right (except for curve A). In the

cases of *Stolephorus* and anchovy, these anomalies were relatively minor and could reasonably be attributed to selective sampling of animals with subnormal avoidance ability. In the case of skipjack, however, this anomaly is more pronounced.

A more likely explanation for the two-part curves of Figure 10 is the construction of the Cobb trawl, which is lined with netting of two different mesh sizes: 19 mm stretched mesh of 9-thread (210 denier) nylon netting in the forward sections, with 6.4 mm stretched mesh 6-thread (210 denier) nylon netting at the cod end (Higgins, 1970). This 3-fold difference in mesh size corresponds with a nearly 3-fold difference in the size of skipjack which makes up the two components of the catch (100% apparent mesh retention at lengths greater than 15.5 mm and 37.5 mm, respectively, from curve B of Figure 10). The Cobb trawl is, in effect, two distinct nets which happen to be rigged in tandem. The openings of the trawl and its cod end during a tow are estimated to have radii of about 4 m and 1.5 m, respectively, so that their mouth areas differ by a factor of seven. The volume of water filtered by the cod end should thus

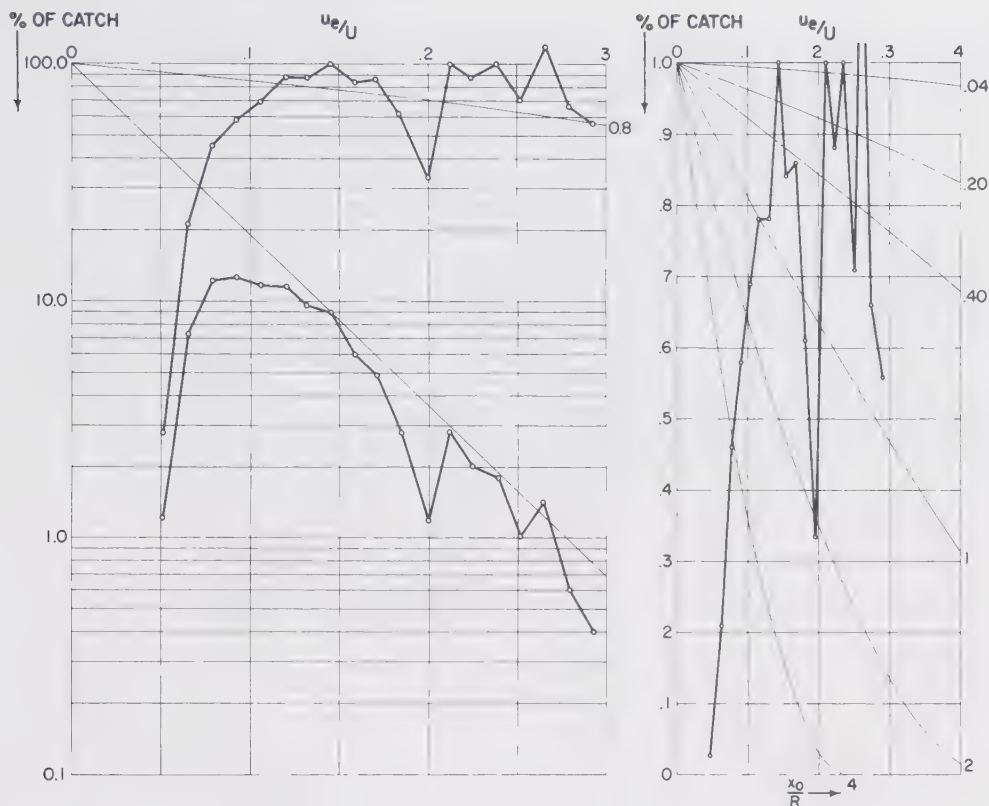


FIGURE 9.—One possible analysis of skipjack catch data, Figure 8, assuming that the length-frequency curve is determined by population density. Left panel: Lower curve, speed-frequency data, Figure 8. The straight line represents a hypothetical population density curve. Upper line shows P_c obtained by correcting catches for population changes. Right panel: Values of P_c from left panel, plotted on linear coordinates.

be somewhat less than one-seventh of the volume sampled by the trawl, because of the increased resistance to flow of the finer mesh. Catches of the six largest class intervals of skipjack all exceeded the "expected" catch (theoretical curve for $x_0/R = 4$) by factors of seven or more, as would be expected if in fact these larger fish were captured by the main body of the trawl, rather than by the cod end.

The evidence suggests that curve B on Figure 10 represents a reasonable analysis of skipjack catches with the Cobb trawl. This implies that avoidance and mesh losses are dominant factors determining the size-frequency curves (Figure 8). The largest skipjack, 31.5 to 43.5 mm in length, were captured by the main body of the Cobb trawl, with P_c values between 0.05

and 0.009. Their reaction distance, x_0 , was $3R$, or some 12 m. Some losses through the coarse mesh are apparent for animals smaller than 39.5 mm in length. Skipjack smaller than 31.5 mm in length were captured by the cod end of the trawl, at P_c values ranging from about 0.3 to 0.03, corresponding to reaction distances of $4R$, or 6 m. Some losses through the finer mesh are apparent for animals smaller than 17.5 mm; estimated mesh losses reach 96% for animals 7.5 mm in length. As was pointed out earlier, the above estimates of reaction distances are dependent on the assumed escape speeds, 10 body lengths per second. If the animals move faster than this, x_0 values will diminish proportionately, and vice versa.

Estimates of P_c are not affected by escape

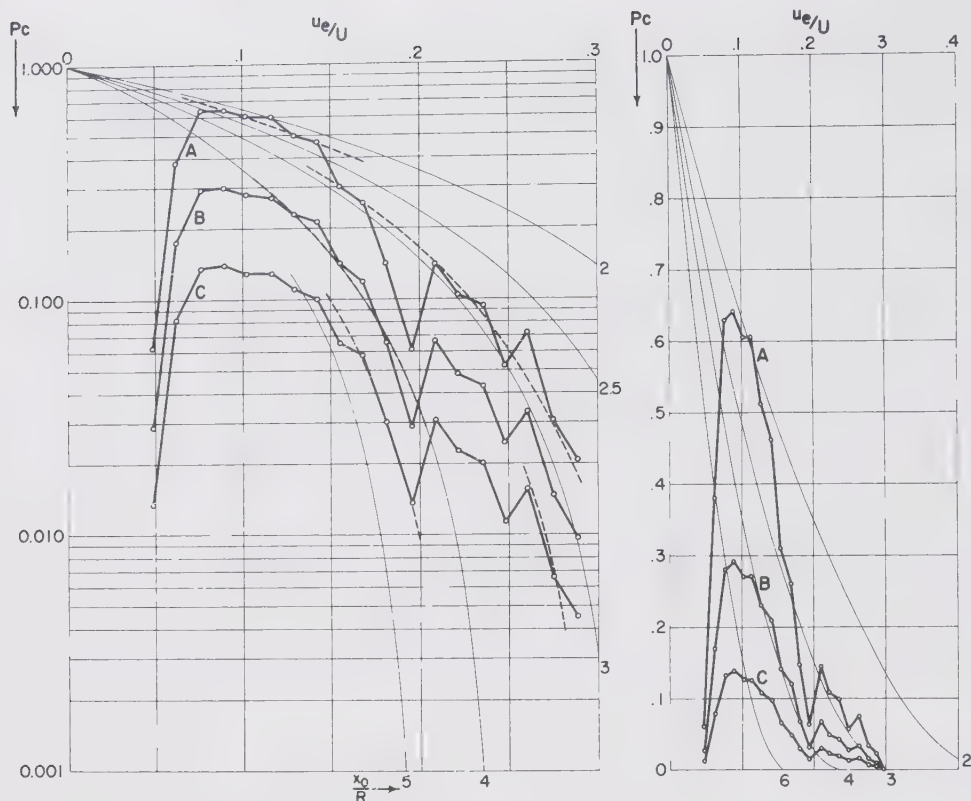


FIGURE 10.—Alternative analysis of skipjack data from Figure 8, assuming constant population density. Left panel: Three possible choices of fit between catch data and theoretical curves of P_c at constant x_0/R . Curve A shows fit for best sampled class intervals. Curve B shows fit for midrange class intervals. Curve C shows fit for regions of maximum slope. Right panel: P_c curves from left panel, plotted on linear coordinates.

speed assumptions, so the analysis yields usable estimates of population abundance of skipjack larvae and juveniles between 17.5 and 43.5 mm in length, if population structure is not important. From curve B of Figure 10, N_0 is 40% (of 499) or 200 individuals per class interval, as can be seen by placing the “% of catch” scale of Figure 9 in the proper position on Figure 10. Since abundance apparently does not seriously affect the length-frequency curve, each of the 19 class intervals sampled must also represent a population of about 200 individuals. Thus the sample of 510 skipjack was taken from a population of about 3,800, an overall catch efficiency of 13%. The total catch resulted from 41 effective tows (out of 74), an average catch per effective tow of 12.3. Accordingly, the popula-

tion sampled by the Cobb trawl must have numbered roughly 94 skipjack per effective tow, to yield the observed catches at 13% efficiency. By far the greatest number of skipjack were caught by the cod end of the trawl, so the volume effectively sampled was not more than 230,000 m³ (100% filtering efficiency). This leads to an estimated mean population density for larval and juvenile skipjack of one fish per 2,500 m³, in areas where skipjack were present during the three *Townsend Cromwell* equatorial cruises.

Since P_c is by definition a minimum probability of capture, reference to equation (3) shows that the above estimate of mean population density (during a tow) represents a maximum value. On the other hand, of course, the skipjack probably were not randomly distributed, so that

a 6-hr tow doubtless underestimates their actual (as opposed to mean) population density by integrating over a 33-km distance.

Finally, two of the four species discussed here were sampled in a manner which permits use of equation (8) to estimate values of K (the product $x_0 u_e$). Anchovy were sampled with two different nets at one speed of tow, and *B. stilbius* were sampled with one net at two ranges of speed. Table 3 shows values of K calculated for these two species. For any one choice of speeds, values of K for *B. stilbius* are nearly constant within the class intervals where fish were retained by the mesh and caught in numbers large enough to yield useful estimates of C_1/C_2 , the ratio of catches obtained at the two speeds. Values of K for anchovy, on the other hand, were not constant. The latter result is not surprising, since widely different values of x_0 were obtained for the 1-m net and the IKMT whereas u_e would not be expected to differ for the two nets. Accordingly, the product of $x_0 u_e$ should not be the same for both nets, which violates the basic assumption used in calculating K with equation (8).

When values of K from Table 3 are used to calculate P_c from equation (7), the results agree with those obtained graphically for *B. stilbius* at the modal speeds, but not for anchovy. Apparently the calculated values of K for anchovy in Table 3 are too low, since they yield values of P_c which are too high, corresponding to values expected for reaction distances of about 2 to 3 m for both nets. Until avoidance behavior

is better understood, equation (8) should be used with caution.

SUMMARY AND CONCLUSIONS

The ideal sampler for plankton and nekton is one whose selective characteristics are known to be appropriate, qualitatively and quantitatively, for the problem under study. Major factors determining the selectivity of towed-net samplers are avoidance and mesh selection, both of which are strongly dependent on species, size or stage of development, and physical condition. Thus the theory of towed-net selectivity must be based on a combination of general principles and detailed knowledge of the physical characteristics and behavior of each species of interest, and of each net design as well.

This preliminary study deals with one aspect of selectivity: the basic principles of avoidance. A theoretical equation is derived for P_c , the minimum probability of capture, for animals which respond individually to an oncoming sampler by attempting to dodge. The theory is based on the amount of time animals allow themselves for avoiding the net, the animal's speed relative to the net, and the geometry of the encounter. Animals are characterized by their reaction distance, x_0 , and their escape speed, u_e . The net is characterized by the radius of its mouth opening, R , and its speed through the water, U . Equations (5) and (6) show the theoretical relationships between these variables and P_c ; Figure 3 illustrates these equations graphically.

TABLE 3.—Values of the product $x_0 u_e = K$ for anchovy and *Bathylagus stilbius*, from equation (8). Anchovy data obtained with two nets towed at one speed, day and night. *B. stilbius* data obtained with one net towed at two speed ranges; K calculated using minimum, modal, and maximum speeds for each range.

Anchovy					<i>Bathylagus stilbius</i>				
Length (mm)	Catch ratios (1-m/IKMT)		K (cm ² /sec)		Length (mm)	Catch ratios (slow/fast)	K (cm ² /sec)		
	Day	Night	Day	Night			Minimum speeds	Modal speeds	Maximum speeds
7.75	0.735	0.764	758	665	47	0.667	5,600	6,500	11,800
8.75	0.492	0.565	1,470	1,240	52	0.222	11,200	13,300	20,700
9.75	0.431	0.524	1,850	1,360	57	0.244	11,000	13,000	20,300
10.75	0.209	0.827	2,410	488	62	0.200	11,500	13,600	21,100
11.75	0.242	0.417	2,280	1,690	67	0.204	11,500	13,500	21,000
12.75	0.847	0.133	435	2,710	72	0.218	11,300	13,300	20,800
					77	0.222	11,200	13,300	20,700
					82	0.238	11,100	13,000	20,400
					87	0.182	11,700	13,900	21,400
					92	0.149	12,100	14,400	21,900

Testing of the theory requires some knowledge of a species' escape speed as a function of size or stage of development and its reaction distance for one or more net designs under various circumstances, so that particular groups of animals in a sample can be associated with the proper values of x_0 and u_e in the theory. If the theory is known to be valid in a given instance, x_0 can be determined once u_e is known.

The theory was evaluated against four selected sets of catch data. Since not enough was known about the swimming ability of the species in question, assumptions had to be made about swimming speed as a function of size for each one. Aside from the major premise used in deriving the theory, that animals which can escape will do so, other assumptions made in carrying out analyses of catch data were: that reaction distance is essentially constant for any one species under a given set of circumstances (one net, towed at one speed, at one time of day) and that the size-frequency curve for a species is determined entirely by mesh losses, avoidance, and the population structure—the number of animals in each size class interval in the population.

The theory was first applied to daytime catches of *Stolephorus purpureus* with a 1-m net. Simultaneous measurements made with a plankton purse seine provided information on the population structure. This nearly ideal set of data permits direct calculation of the sampling efficiency of the 1-m net, so that an absolute test of the present theory could be made. First, the bias due to population structure was removed, by dividing the catch in each class interval by the population in that class interval; this procedure also converts the catch into values of P_c for fish large enough to be completely retained by the meshes, as equation (3) demonstrates. The adjusted catch curve (the solid line labeled C_L/N_L in Figure 4) can be directly compared with theoretical curves from Figure 3 (showing P_c for various values of relative reaction distance, x_0/R), when the length class intervals have been converted to speed class intervals by assuming that the fish swim 10 body lengths per second. Agreement between theory and observation appears to be good, with some exceptions. These may be due to sampling var-

iance, population variance, or failure of one or more assumptions used in matching *S. purpureus* to the theoretical parameters. In the latter case, the anomalies could be accounted for by incompetent avoidance behavior and school response instead of individual reaction to the net.

In the second example, the theory was used to evaluate catches of anchovy by two different nets, a 1-m net and an IKMT, towed at the same nominal speeds. Since population abundance was not determined for anchovy, an additional assumption had to be made: that the catch length-frequency curves were determined primarily by avoidance and mesh losses, as in the case of Hawaiian anchovy, where catches decrease 1,000-fold while the population decreases only by a factor of 10 in the same size interval. With this assumption, catch speed-frequency curves must also be curves of relative P_c as a function of size, or speed. Fitting the observed values to the theoretical P_c curves (Figure 5) yields a unique value for population density in each class interval, numerically equal to the catch at $P_c = 1.0$. For the anchovy, population densities of 75 and 60 animals per 100 ml wet plankton were obtained for the two samples analyzed by this method. In this case agreement between theory and observation, and between samples, seems excellent. Except for night tows with the 1-m net, values of P_c do not exceed 0.40 for the 1-m net and 0.12 for the IKMT. The only significant deviations from theory occur at smaller class intervals, where mesh losses are important. Mesh retention can be estimated quantitatively by extrapolating the theoretical curve toward smaller class intervals, for comparison with observed catches, as illustrated on the right-hand panel of Figure 5.

The third example makes use of length-frequency data for *Bathylagus stilbius* caught with an IKMT towed at two different ranges of speed. In this case, no satisfactory fit could be achieved for all larger class sizes of both sets of tows, when treated as a unit. If instead the analysis is performed using only one class interval at a time from the two sets of tows, as shown in Figure 7 and Table 1, the cause of the difficulty becomes clear. The estimated population densities have almost as great a range as do the

catches. Therefore the length-frequency curves are primarily determined by population structure, not avoidance. However, avoidance does account for the fact that faster tows caught nearly five times as many fish. Table 1 shows that P_c remained essentially constant for each set of tows over a wide range of class intervals, with values of about 0.3 for the fast tows and 0.07 for the slower ones.

The final example illustrates the use of avoidance theory for analysis of a more typical set of catch data: larvae and juveniles of the skipjack tuna caught with one net towed at one speed. The simplest way to account for the skipjack data is to assume that avoidance was more important than population structure (Figure 10). The Cobb pelagic trawl used to sample skipjack had two sizes of mesh, differing by a factor of three; the smaller mesh was used to line the cod end of the Cobb trawl. Catches of skipjack with this net fall into two groups differing in size by a factor of about three, suggesting that this trawl acts as two nets fishing in tandem. The large mesh forward end catches the largest fish, with a maximum P_c of the order of 0.03. The cod end catches smaller fish, with maximum P_c values of about 0.3. Fish of intermediate size are able to dodge the cod end but some 10% to 50% of these fish (depending on size) were retained by the larger meshes.

Analysis of four test cases leads to the conclusion that the elementary avoidance theory developed here does in fact provide reasonable interpretations of some samples obtained with towed nets. The theory's major virtue is its ability to provide relatively unambiguous estimates of probability of capture and thus of animal abundance in nature, which are not dependent on the accuracy of assumptions about swimming speeds or reaction distances. Even when the theory fails to account for observed features of the catch, it provides useful insight into the reasons for such failure and some indication of their magnitude. This is most clearly evident for losses through the mesh, but failures of the theory, or of the assumptions used in applying it, are also responsible for evidence uncovered here of incompetent avoidance behavior by smaller animals, effects of schooling on avoidance

success, and the fact that avoidance has only a minor effect on the length frequencies of *B. stilbius* samples. Given our present lack of knowledge of the behavior of animals when confronted by towed samplers, it might even be said that anyone using this theory should be most cautious in precisely those cases where the theory apparently works best. A case in point is the analysis of anchovy data presented on Figure 5. Agreement between observations and theory is relatively good in this case, so that it might be easy to forget that the slope of both curves, and the apparently valid estimates of reaction distance obtained from their slopes, depend entirely on the assumed relationship between the anchovy's length and its swimming speed. Similarly, Figure 7 shows the errors which can result from assuming that the speed of the net is constant. The best contribution to the study of plankton and nekton which the present theory could make is to stimulate further research which will make the theory obsolete.

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Distribution of Forage of Skipjack Tuna (*Euthynnus pelamis*) in the Eastern Tropical Pacific¹

By

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ABSTRACT

The fishery for skipjack tuna (*Euthynnus pelamis*) in the eastern Pacific Ocean might be extended if offshore areas of high skipjack abundance were known. One would expect the numbers of skipjack in these offshore areas to be related to the distribution of known skipjack forage organisms in the micronekton. The EASTROPAC oceanographic cruises yielded net-caught micronekton samples over large parts of the eastern tropical Pacific during seven successive 2-month periods. From these samples, the occurrence of organisms known to be prey of skipjack was expressed as ml/1000 m³. Charts of night and day concentrations in the upper 200 m were produced for each of the seven periods.

In the region from long 92° to 119° W the major areas of maximum concentration of potential skipjack forage remained essentially constant during most periods. Two of these areas lie parallel to the equatorial upwelling zone—one just to the north, the other just to the south. Another zonal area of abundant forage generally occurs between lat 6° and 14° N. Forage is also frequently abundant between lat 14° and 20° N and long 107° and 119° W.

The concentrations of skipjack forage in these areas are comparable with those in nearshore parts of the eastern tropical Pacific, where the present skipjack fishery occurs. The abundance of skipjack in the forage-rich offshore areas might therefore be sufficient to support commercial fishing operations. Sea-surface temperatures are generally suitable for skipjack in those areas. On three recent crossings of the equatorial region at about long 119° W, skipjack appeared to be abundant in the first three areas of high forage concentration mentioned above.

INTRODUCTION

Most of the fishery for skipjack tuna (*Euthynnus pelamis*) in the eastern tropical Pacific lies within a few hundred miles of the American coast. Skipjack taken in these waters probably represent adolescent stages of a migratory population which breeds in the central

tropical Pacific, and is not being fully exploited (Rothschild, 1965; Joseph and Calkins, 1969). The United States tuna fishery in the eastern tropical Pacific may become increasingly dependent upon skipjack. The tropical Pacific tuna fleet continues to grow in size in spite of the fact that the fishery for yellowfin tuna (*Thunnus albacares*) is regulated, and other than skipjack there is no equally available and

¹This work was supported by the National Marine Fisheries Service (former Bureau of Commercial Fisheries), both directly and through Contracts 14-17-0007-458, 14-17-0007-742, 14-17-0007-963, and 14-17-0007-2311 with the Institute of Marine Resources, University of California. It was part of the research of the Scripps Tuna Oceanography Research Program of the Institute of Marine Resources.

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commercially marketable species. However, the fishery for skipjack has not been able to extract more than 265 million pounds (120,-200 metric tons) from the coastal areas and the neighboring islands in any year in the period since the yellowfin fishery was first regulated in 1966, and the yearly catch from those areas has been as low as 127 million pounds (57,600 metric tons) (Inter-American Tropical Tuna Commission, 1970).

Thus, new fishing grounds for skipjack are needed. Attention has been focused on the possibility of extending the fishery from the coastal areas, where present effort is mostly confined, out into the offshore areas to the west, where the abundance of skipjack is unknown. Because of their proximity to the spawning grounds, some of these offshore areas may yield larger fish than are taken near shore, and the larger fish are better suited for canning. Miyake (1968) showed that skipjack, including some of large size, occur throughout the tropical Pacific. It would aid the U.S. tuna fleet to know where in the unfished offshore regions of the eastern tropical Pacific skipjack are most abundant, and which areas offer the most potential as a commercial skipjack fishery.

A first step in determining the distribution of these offshore skipjack was to identify areas where environmental conditions are most suitable for them. The cooperative EASTROPAC oceanographic expedition of 1967-1968, which was coordinated by the National Marine Fisheries Service (former Bureau of Commercial Fisheries), was designed to accomplish this and other objectives.

Previous investigations indicate that adult tunas aggregate where food is abundant in waters that are within certain ranges of tem-

perature, which vary from species to species (Blackburn, 1965). Specifically, this has been confirmed for skipjack and yellowfin tuna in the fishery area off Baja California in the eastern Pacific (Blackburn, 1969). In the eastern Pacific fishery region, most skipjack aggregations occur in water between approximately 20° and 29° C (Williams, 1970). Skipjack are fished by U.S. fishermen at or near the sea surface, so surface temperatures are sufficient to identify areas where temperature is suitable. Charts of mean monthly surface temperature show that most parts of the eastern tropical Pacific have temperatures suitable for skipjack nearly all the year (Wyrski, 1964), so that a knowledge of temperature distribution, in itself, would not show us where skipjack are concentrated. However, consideration of temperature information in conjunction with the distribution of skipjack forage organisms might help identify areas of potential skipjack abundance.

Alverson (1963) and Waldron and King (1963) listed the prey organisms of skipjack tuna in the eastern tropical Pacific and central Pacific, respectively. Nakamura (1965) gave similar information for skipjack of the Marquesas and Tuamotu Islands, between about long 135° and 155° W in the south Pacific. Most of the skipjack stomachs that Alverson (1963) studied were collected within about 500 miles of the tropical American Pacific coast. The stomachs studied by Waldron and King (1963) were collected broadly between long 150° and 180° W. The results of skipjack stomach content studies are summarized in Table 1. Alverson (1963) and Nakamura (1965) noted a tendency for skipjack over 60 cm long to have a smaller proportion of crus-

Table 1. Summary of results of stomach content analyses of skipjack tuna.

References	Number of stomachs	Percentage composition			Percentage frequency		
		Crustaceans	Fishes	Cephalopods	Crustaceans	Fishes	Cephalopods
Alverson (1963)	2317	59	3	37	76	36	13
Waldron and King (1963)	707	4	75	20	41	76	40
Nakamura (1965)	603	-	-	-	72	77	24

taceans in the diet than smaller skipjack in some areas, but Waldron and King (1963) found no significant difference in the representation of total crustaceans, fishes, or cephalopods in skipjack under and over 60 cm.

The prey of skipjack tuna form part of the assemblage of active pelagic fishes, cephalopods, and crustaceans about 1 to 10 cm in size, which we call micronekton. Micronekton collections were taken during EASTROPAC cruises, and the organisms known or expected to be prey of skipjack, based on the above-cited food habit studies, were sorted out and measured volumetrically. This report describes the distribution of the total of these skipjack-forage organisms as a contribution to skipjack ecology. Other aspects of the study of EASTROPAC micronekton samples, including organisms that are not eaten by skipjack, are described elsewhere (Blackburn et al., 1970).

MATERIAL AND METHODS

Seasonally repetitive oceanographic observations were made in the eastern tropical Pacific between lat 20° N and 20° S, bounded in the east by the American coast and in the west usually by long 119° W. During EASTROPAC, seven cruises were made of approximately 2 months each: February-March 1967, April-May 1967, June-July 1967, August-September 1967, October-November 1967, December 1967-January 1968, and February-March 1968. Figures 1(A, B) through 7(A, B) show the extent of the coverage in the eastern tropical Pacific during the successive periods. Most of the data were collected west and south of the existing skipjack fishing areas near the American coast.

We sampled micronekton on these cruises in oblique hauls of a large net, 1.5 m square at the mouth, with a uniform mesh size that retains animals ≥ 1 cm but not smaller (Blackburn, 1968; Jerde, 1967). The micronekton samples were taken from the surface to a depth of approximately 200 m, with ship speeds during the hauls ranging from 4.0 to 6.4 knots. The volumes of water strained were estimated as described by Blackburn et al. (1970). The displacement volume of the total skipjack forage

was measured and standardized in ml/1000 m³ of water strained for each haul. Generally, two micronekton hauls were made during each 24-hr period, one usually close to local apparent noon and the other usually close to local midnight. The day-time catches were usually about one-tenth the size of the night catches, by volume. Similar day-night differences have been observed in other micronekton studies and have been shown to be due to net avoidance and vertical migration of organisms (Pearcy and Laurs, 1966). Because of their larger size, the night samples may give a better representation of the total amounts of skipjack forage present. However, it was considered important to sample in the daytime also because skipjack probably do much of their feeding during hours of daylight (Nakamura, 1962). In addition, two hauls per diel period were expected to give better resolution of the positions of maxima and minima of forage, than one haul. An estimate of sampling variability for night catches is given by a series of 11 catches made during one night at approximately the same geographical position. The coefficient of variation of the total micronekton volume was 20%.

The following components of the micronekton net catches are regarded collectively as skipjack forage: *Vinciguerria* spp., all epipelagic fishes, *Pleuroncodes* spp., all other crustaceans, and all cephalopods. The following other components were not considered part of skipjack forage: leptocephali, all mesopelagic fish except *Vinciguerria*, and large watery plankters such as salps and medusae. Fishes with photophores were called mesopelagic, most others epipelagic. Leptocephali are transparent and would probably be hard for skipjack to see, and there is no evidence that skipjack eat them. Mesopelagic fishes mostly occur near the surface at night, and with the very important exception of *Vinciguerria*, they are seldom an important item in skipjack stomach contents in the eastern or central tropical Pacific (Alverson, 1963; Waldron and King, 1963; Nakamura, 1965). The epipelagic fishes, crustaceans, and cephalopods have not yet been completely sorted to families. They may therefore have included some families which Alverson, Waldron and King, and Nakamura did not find

in skipjack stomachs. However, we have no reason to think that any member of these families would not be eaten since tunas are opportunistic feeders within their sensory and behavioral limitations (Blackburn, 1968).

Catches of micronekton by large nets and small midwater trawls give imperfect estimates of the availability of tuna forage (King and Iversen, 1962; Laurs and Nishimoto⁴). Highly mobile epipelagic fishes and cephalopods may avoid the net. Some small components of the forage, such as euphausiids, may pass through the meshes of some nets, although not the net used in this study. Nevertheless, our measurements of standardized displacement volume of potential skipjack forage no doubt validly distinguish areas where forage is rich and poor and are the best relative estimates of potential skipjack forage that can be produced at this time.

RESULTS

Figures 1(A)-7(A) and 1(B)-7(B) show the distribution of potential skipjack forage as indicated by night and day micronekton samples, respectively, collected on the seven EASTROPAC cruises. Contours represent concentrations of the forage organisms as indicated by the collections; the night values are greater than the day values on similar contours by a factor of 10, e.g., 80 ml/1000 m³ (night) and 8.0 ml/1000 m³ (day). Heavy dashed lines in the figures indicate positions of zonally (latitudinally) oriented maxima. Where the position of such a line is not clearly justified by the contours, it is based on differences in actual concentration within the same contour interval.

It is convenient to mention first the features of forage distribution for the area west of long 92° W. Most of this part of the EASTROPAC area is not presently fished for skipjack, and the positions of forage maxima may indicate where skipjack are most abundant. The area east of long 92° W is discussed secondly.

Area West of Long 92° W

The most conspicuous maximum occurs in a zonal band between lat 0° and 5° N. It is evident on at least two adjacent sampled meridians in each figure except 6(B). It appears to be well developed for both night and day forage at all seasons. Another maximum sometimes occurs between lat 2° and 8° S. Figures 1(A), 1(B), 4(B), and 6(A) show it on at least two adjacent meridians. It generally has lower concentrations over a smaller area and is less continuous zonally than the maximum just north of the equator. The data do not justify any statement about seasonal changes in its development. A zonal maximum also occurs with some regularity between 6° and 14° N. It is evident on two or more adjacent meridians in each figure except 4(A), 5(A), and 6(B). This maximum is generally more evident in the charts of the distribution of day forage than in the charts of night forage. There appears to be no great seasonal change in its development, and forage concentrations are generally lower than in the northern equatorial maximum.

High concentrations of forage appear in several of the charts in the northwestern part of the area, approximately north of lat 14° N and west of long 107° W [Figs. 1(A), 2(B), 4(A), 4(B), 5(B), and 7(A)]. For some cruises they are more conspicuous in the night forage than in the day forage; for others, the reverse. Other maxima appear irregularly in generally smaller areas. Forage concentrations in the southern part of the area, and in the northwestern part with the exceptions mentioned above, tend to be low.

Area East of Long 92° W

In the area east of long 92° W, which was sampled less frequently than the more offshore area, the main maxima are coastal. They vary in position, however, not only between cruises but also between night and day forage distributions for the same cruise. High values are usually observed off Peru and/or Ecuador, and moderate values sometimes occur in the region of the Panama Bight. Except near Peru, the maximum concentrations near the coast are no

⁴Laurs, R. M., and R. N. Nishimoto. Food of troll-caught Pacific albacore, *Thunnus alalunga* (Bonnaterre), and an evaluation of midwater trawl catches as a measure of potential albacore food. National Marine Fisheries Service, Fishery-Oceanographic Center, La Jolla, Calif. 92037. Manuscript.

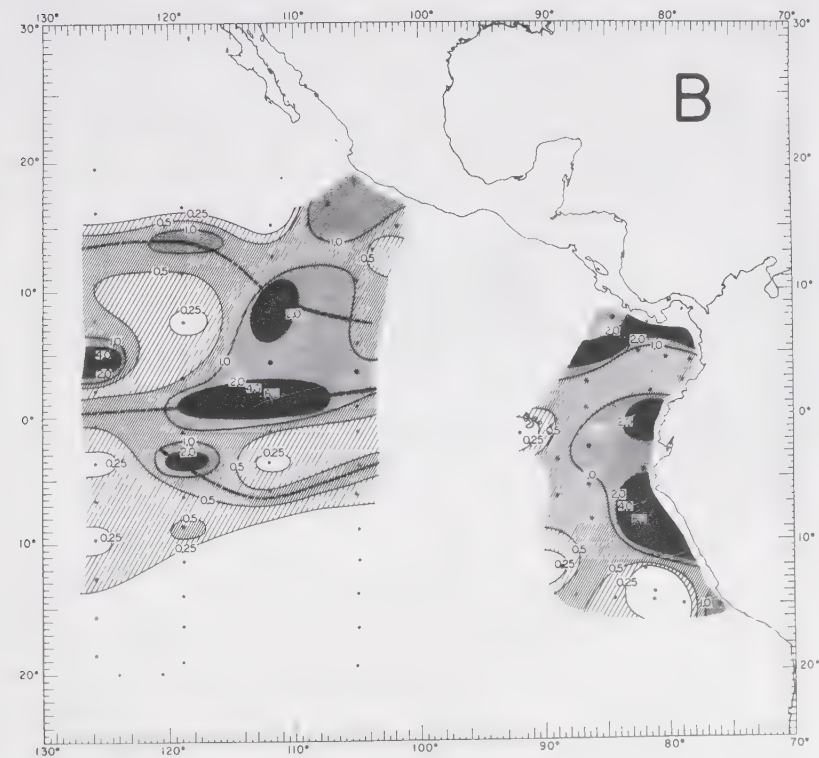
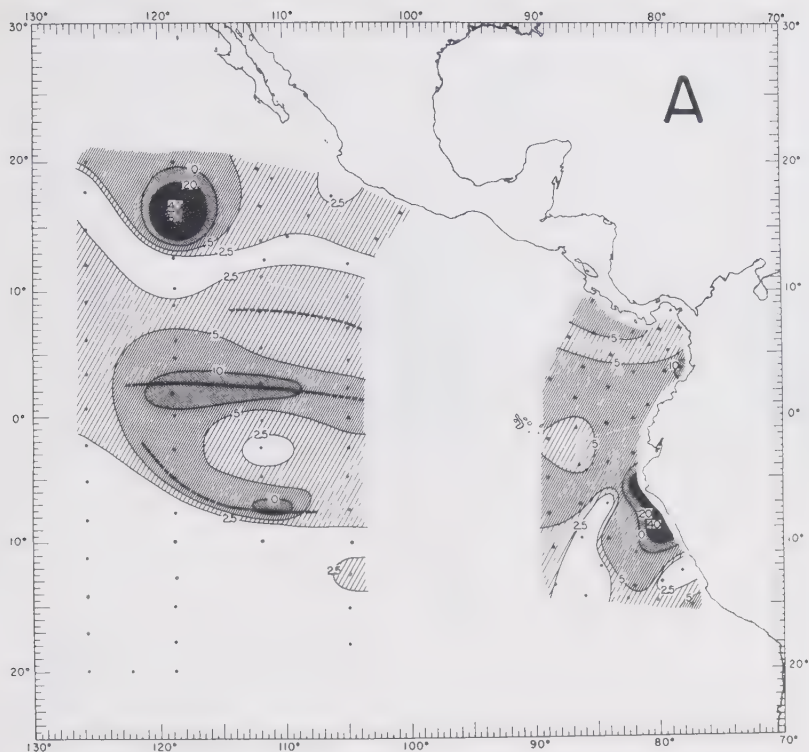


Figure 1.—Concentrations of skipjack forage measured in the first cruise period of the EASTROPAC expedition, February-March 1967, in ml/1000 m³: (A) at night stations; (B) at day stations. Heavy dashed lines indicate positions of zonally oriented maxima.

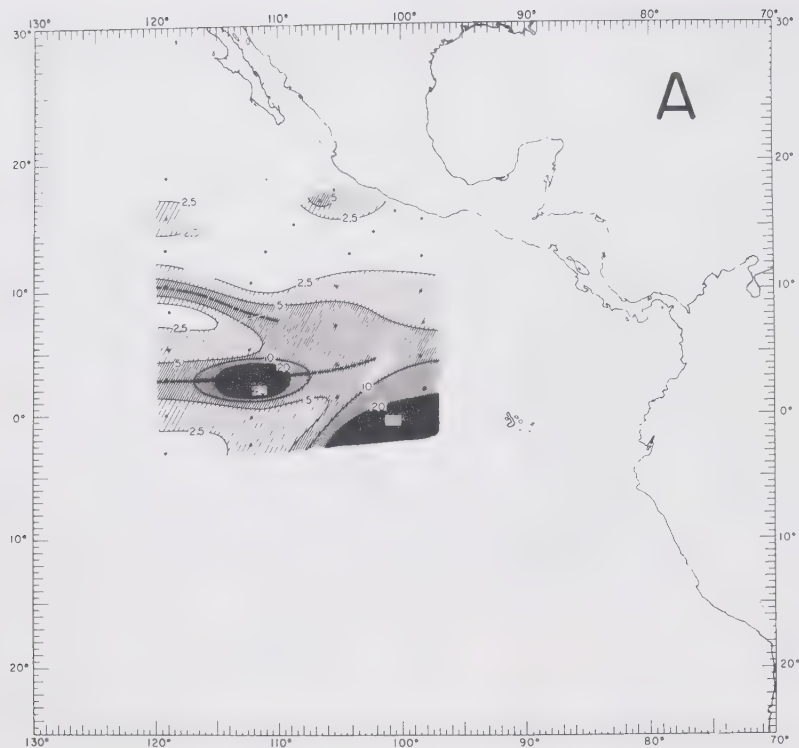
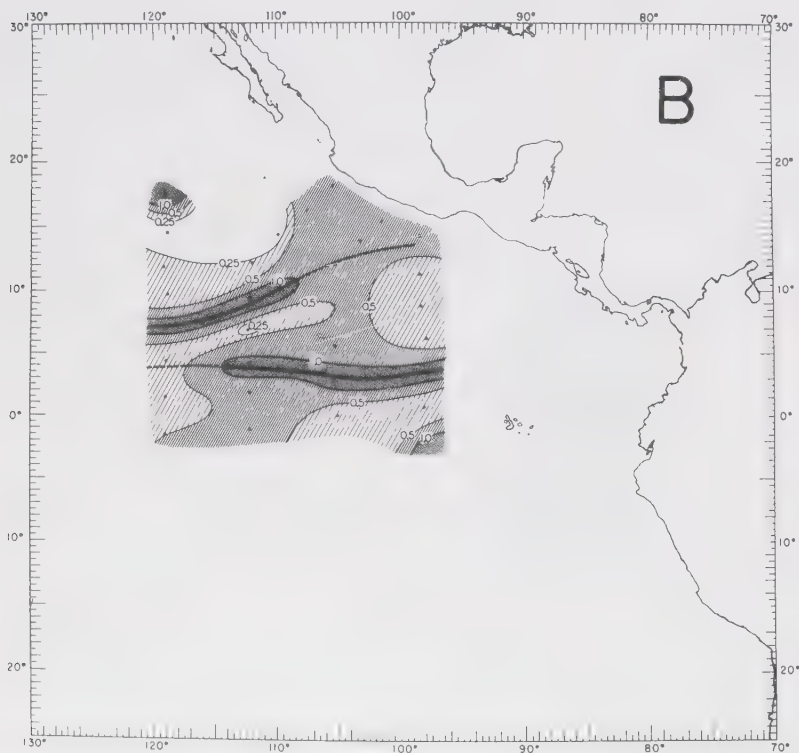


Figure 2.—Concentrations of skipjack forage measured in the second cruise period of the EASTROPAC expedition, April-May 1967, in ml/1000 m³: (A) at night stations; (B) at day stations. Heavy dashed lines indicate positions of zonally oriented maxima.



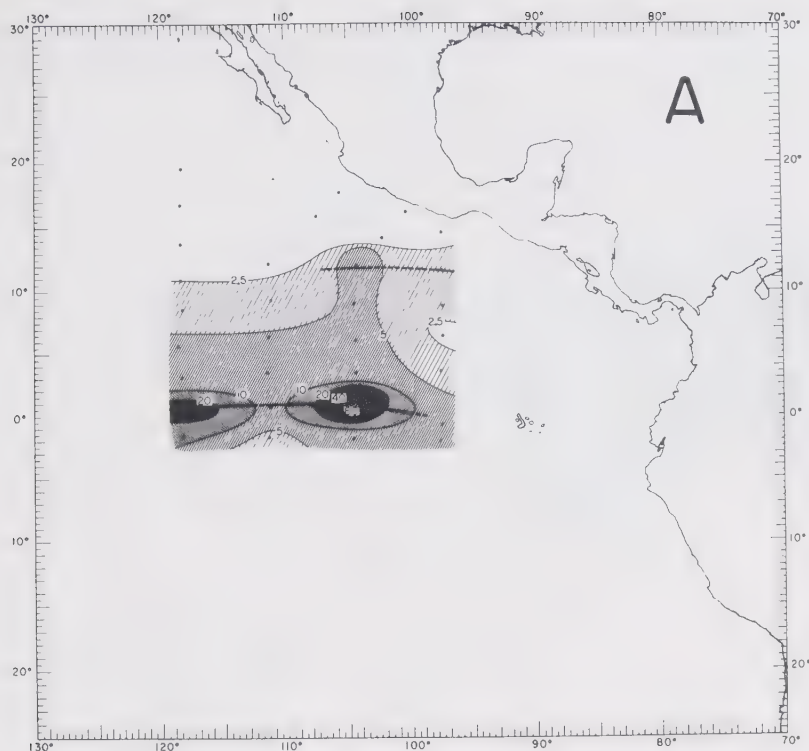
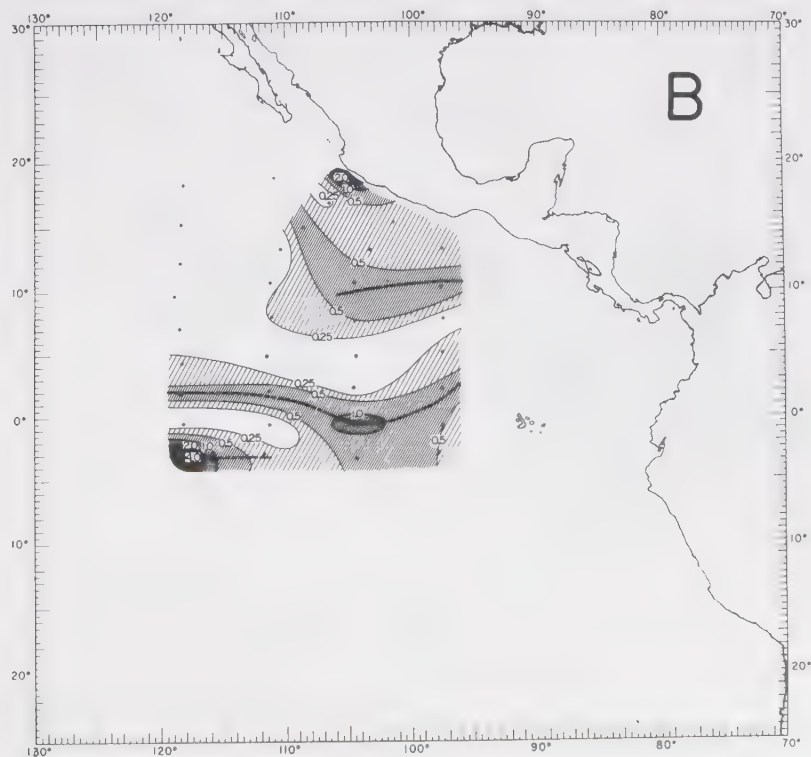


Figure 3.—Concentrations of skipjack forage measured in the third cruise period of the EASTROPAC expedition, June-July 1967, in ml/1000 m³: (A) at night stations; (B) at day stations. Heavy dashed lines indicate positions of zonally oriented maxima.



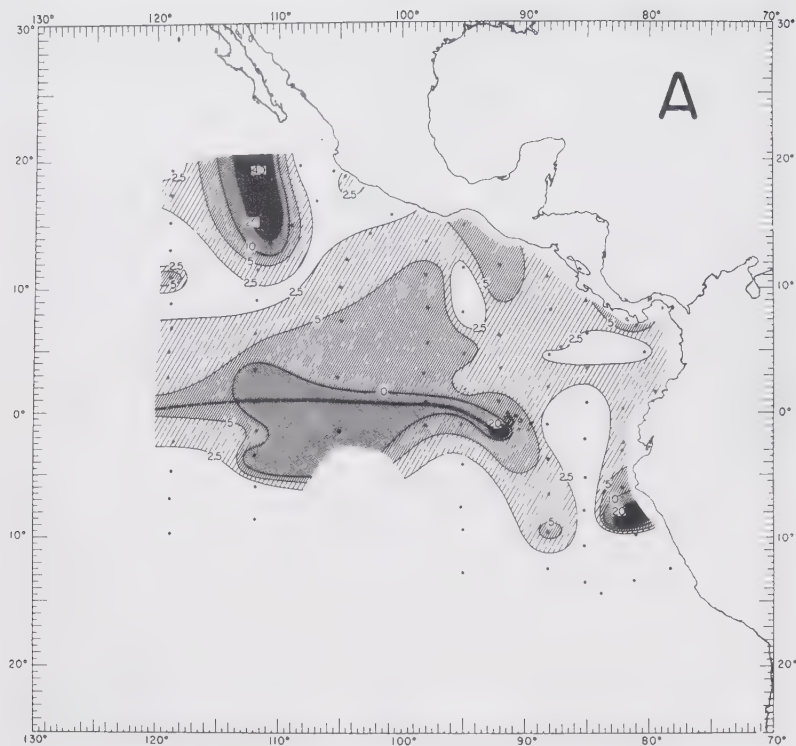


Figure 4.—Concentrations of skipjack forage measured in the fourth cruise period of the EASTROPAC expedition, August-September 1967, in ml/1000 m³: (A) at night stations; (B) at day stations. Heavy dashed lines indicate positions of zonally oriented maxima.

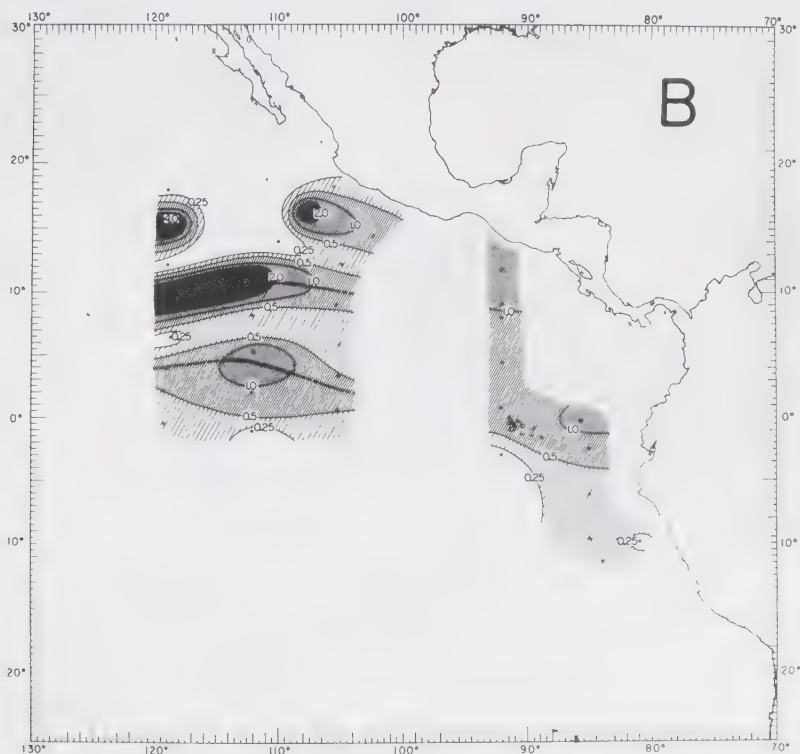
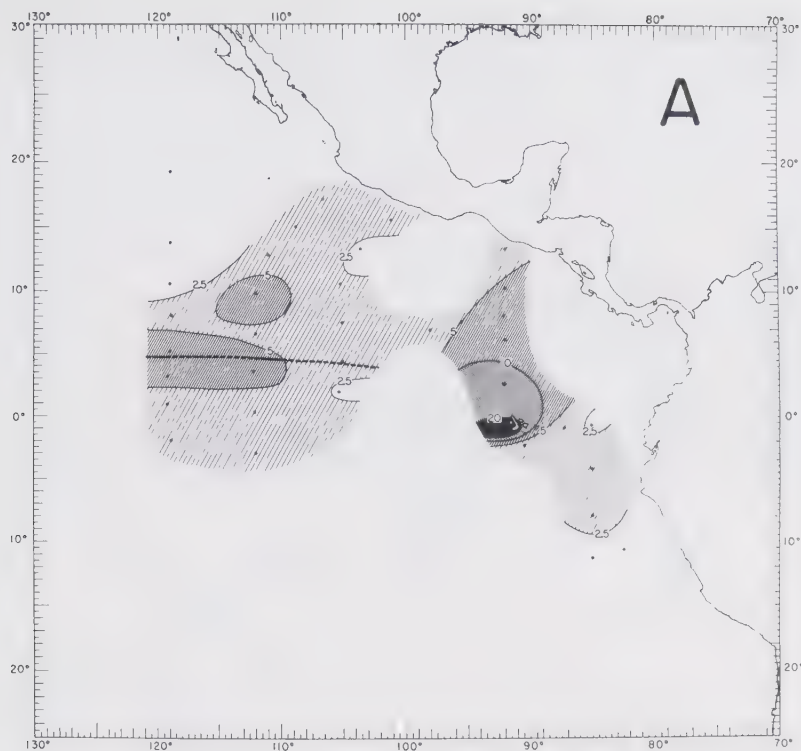


Figure 5.—Concentrations of skipjack forage measured in the fifth cruise period of the EASTROPAC expedition, October-November 1967, in ml/1000 m³: (A) at night stations; (B) at day stations. Heavy dashed lines indicate positions of zonally oriented maxima.

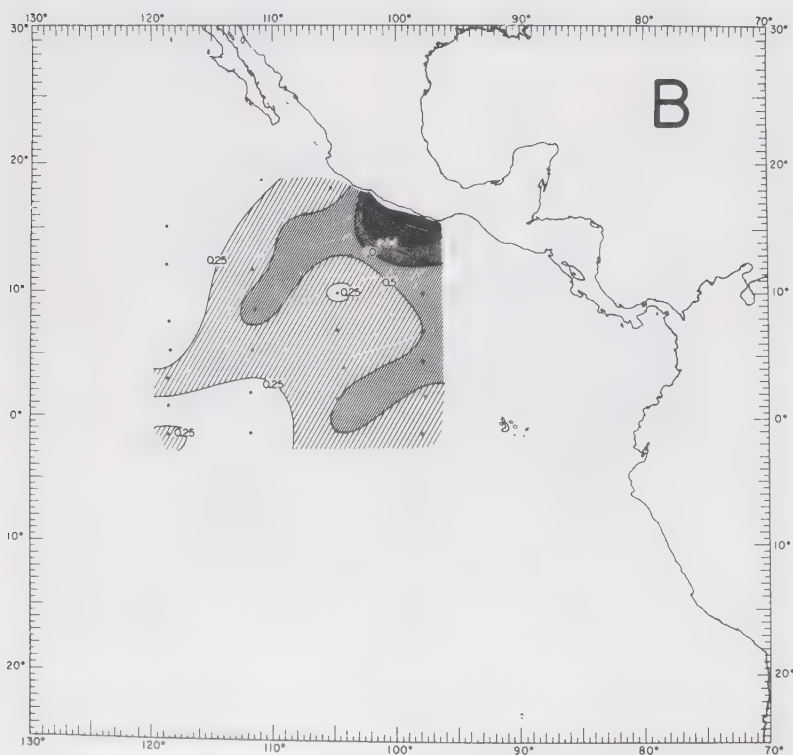
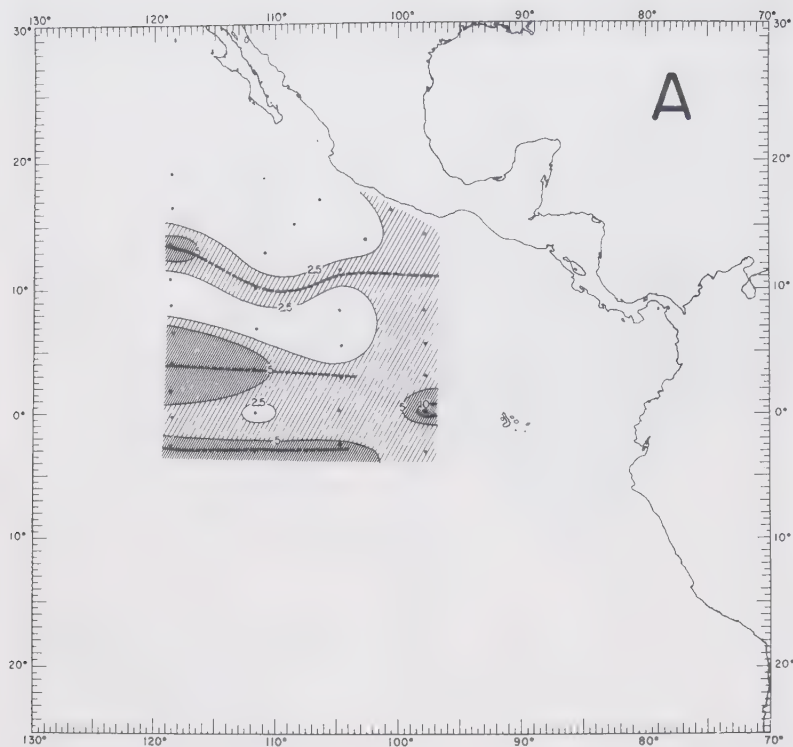


Figure 6.—Concentrations of skipjack forage measured in the sixth cruise period of the EASTROPAC expedition, December 1967-January 1968, in ml/1000 m³: (A) at night stations; (B) at day stations. Heavy dashed lines indicate positions of zonally oriented maxima.

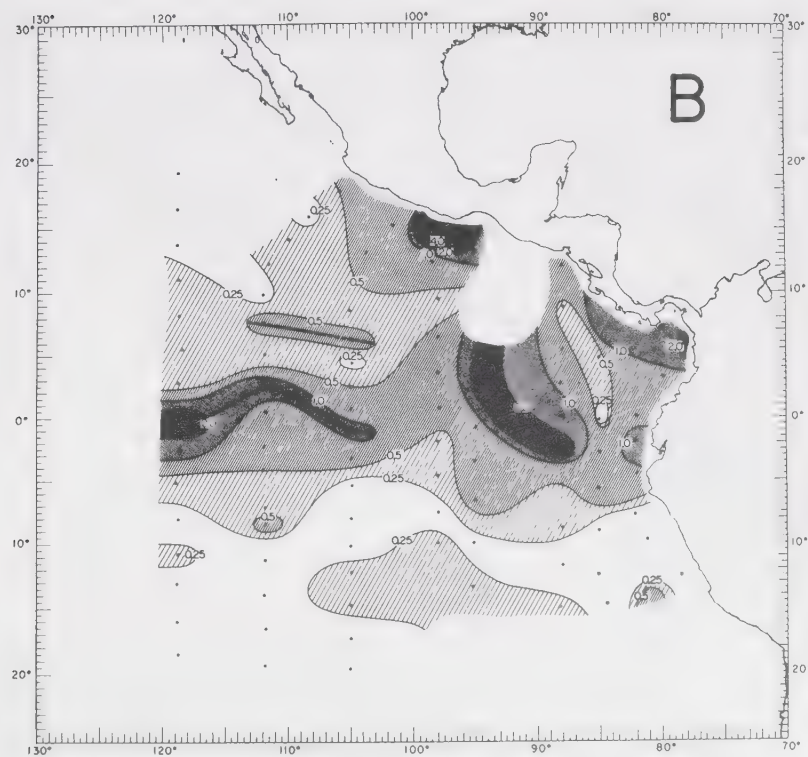
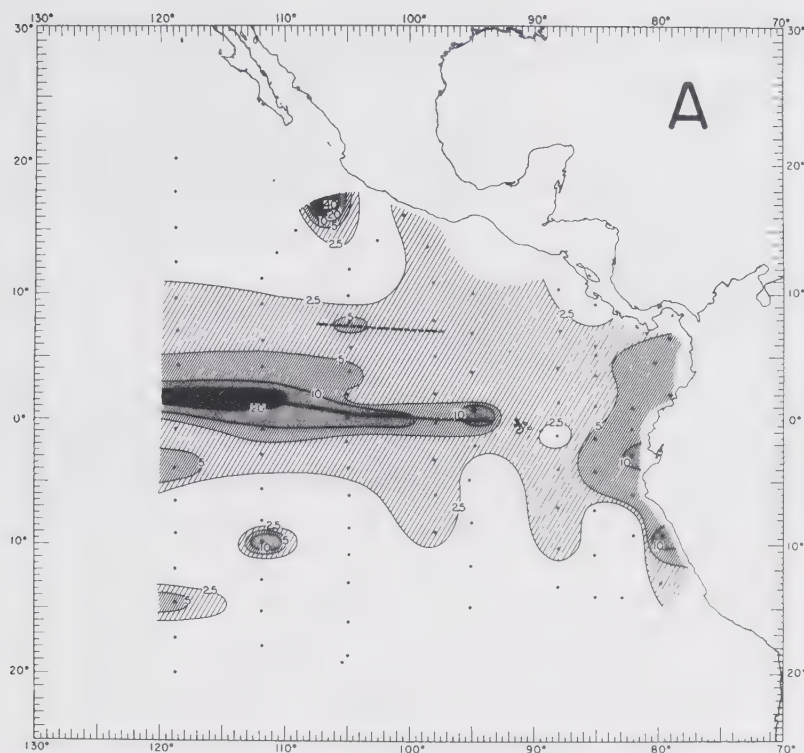


Figure 7.—Concentrations of skipjack forage measured in the seventh cruise period of the EASTROPAC expedition, February-March 1968, in ml/1000 m³: (A) at night stations; (B) at day stations. Heavy dashed lines indicate positions of zonally oriented maxima.

higher and sometimes lower than maximum concentrations west of long 92° W.

A variable area of low forage, centered at about lat 1° S between long 85° and 92° W, is recognizable in Figures 1(A), 1(B), 4(A), 4(B), 5(A), 7(A), and 7(B). It may extend farther north, as in Figure 7(B), or south, as in Figure 4(A). Another minimum, oriented more or less zonally, appears in Figures 1(A), 1(B), 4(A), and 7(B). It occurs between lat 0° and 7° N, long 90° W, and the coast.

Tables 2 and 3 show the percentage volumetric composition of night and day skipjack forage, respectively, in the regions of the above-mentioned maxima, in terms of the five categories of organisms for which data are available. The most striking difference is between

the forage in the maximum in the northwestern part of the area, which consists predominantly of the pelagic galatheid crustacean *Pleuroncodes planipes*, and that in the other maxima, where other crustaceans predominate. The taxonomic groups of forage animals in the maximum at lat 6°-14° N are more equal in quantity than elsewhere, both by night and day.

DISCUSSION

Skipjack fisheries presently exist in many of the areas where high concentrations of forage were observed on the EASTROPAC cruises. These include 1) along the American coast, 2) in the Galápagos Islands region, centered at about long 91° W and the equator, and 3) in

Table 2. Percentage volumetric composition of night skipjack forage in the areas of the principal maxima in the EASTROPAC region.

Maxima	Components of skipjack forage					
	Vinciguerria	Epipelagic fish	Pleuroncodes	Other crustaceans	Cephalopods	Total
<u>West of 92° W</u>						
2° to 8° S	2.1	3.0		69.4	25.5	100.0
0° to 5° N	1.1	0.3	-	95.3	3.3	100.0
6° to 14° N	3.6	11.5	9.0	61.4	14.5	100.0
North of 14° N, west of 107° W	2.2	1.8	94.6	1.1	0.3	100.0
<u>East of 92° W</u>						
South American coast	1.1	4.2	-	91.5	3.2	100.0

Table 3. Percentage volumetric composition of day skipjack forage in the areas of the principal maxima in the EASTROPAC region.

Maxima	Components of skipjack forage					
	<u>Vinciguerria</u>	Epipelagic fish	<u>Pleuroncodes</u>	Other crustaceans	Cephalopods	Total
<u>West of 92° W</u>						
2° to 8° S	-	0.9	-	93.8	5.3	100.0
0° to 5° N	0.3	0.3	-	87.0	12.4	100.0
6° to 14° N	1.9	0.6	0.6	81.9	15.0	100.0
North of 14° N, west of 107° W	1.0	-	96.0	2.8	0.2	100.0
<u>East of 92° W</u>						
South American coast	-	1.2	-	96.9	1.9	100.0

the Revillagigedo Islands region; between lat 18° and 20° N in the northwestern part of the EASTROPAC area (Joseph and Calkins, 1969; Williams, 1970). We are here concerned with the possibilities of occurrence of abundant skipjack in other, more offshore areas where high concentrations of potential skipjack forage regularly occur and where little or no fishing has been done. These are located west of long 95° W just north and south of the equator, and between lat 6° and 14° N; and in the northwestern part of the area between about lat 14° and 18° N. Since the levels of forage concentration in these unexploited areas are comparable with the maximum levels in the areas that are exploited, they may be equally attractive to skipjack.

There is a broad basis for the expected association of abundant adult skipjack with the high offshore forage concentrations. Skipjack are fairly heavy feeders, eating the equivalent of 15% of their body weight per feeding day of 12 daylight hours when fed to satiation (Magnuson, 1969); therefore, they would be expected to aggregate in productive areas of abundant forage. Also, skipjack are known to be highly mobile animals with maximum swimming speeds in excess of 10 body lengths/sec (Blaxter, 1969) and cruising speeds up to 6 body lengths/sec (Yuen, 1970), clearly able to leave areas in which the forage is sparse in search of richer areas elsewhere. When skipjack migrate between the central and eastern Pacific, they possibly remain in biologically productive latitudes (Williams⁵).

The above-mentioned areas of offshore forage maxima would not be expected to contain skipjack, in commercial concentrations, if surface temperatures were unsuitable, i.e., under 20° or over 29° C. Sea-surface-temperature information for the eastern tropical Pacific (Wyrtki, 1964; La Violette and Seim, 1969; monthly charts issued by the National Marine Fisheries Service, La Jolla, California) indicates that the forage maximum in unfished

areas lying just north of the equator might occasionally be too cold for skipjack at some longitudes west of the Galápagos Islands in the months July through November, although longitudes west of 117° W would probably not be affected. The same might apply to the maximum south of the equator. The maximum at lat 6°-14° N might occasionally be too warm for skipjack in some or all of the areas where we have found it, especially in the months of July through October. If fisheries develop in the areas of these forage maxima, monitoring or forecasting the occurrences of unusually high or low surface temperatures might be useful to fishermen.

The zonal maximum just north of the equator has been observed before, both in the EASTROPAC area and farther west in the central Pacific, by King (1958) and King and Iversen (1962). These authors also observed a second zonal maximum just south of the equator (lat 2° S) on one occasion at long 120° W (but not at 112°), although they did not comment upon it. King (1958) suggested an explanation of the northern maximum based on the work of Cromwell (1953). Northerly and southerly components of water transport result from the equatorial divergence, and because the prevailing winds are from the southeast, the major drift of newly upwelled water is towards the north. As this drifting water becomes older it gets warmer, and this together with its nutrient richness enables it to support large populations of organisms. The organisms at successively higher trophic levels reach their biomass maxima at successively longer intervals of time, and thus of space, from the original upwelling; therefore, the forage maximum will occur some distance north of the center of the equatorial upwelling. We would amend this interpretation to include the situation where the drift of the upwelled water is to the south, whereby a forage maximum may occur south of the equator, although less pronounced than the northern one, as we have observed in this paper. Similar ideas have been expressed by Vinogradov and Voronina (1965).

The zonal maximum of skipjack forage between lat 6° and 14° N may represent a result of high biological production along the ridge in the strong thermocline that occurs in those lati-

⁵Williams, F. Meteorology, oceanography, and migrations of recruit skipjack in the eastern Pacific Ocean. Scripps Tuna Oceanography Research Program, Institute of Marine Resources, Scripps Institution of Oceanography, La Jolla, Calif. 92037. Manuscript.

tudes along the northern edge of the North Equatorial Countercurrent (Wyrski, 1964, 1965). We have observed elsewhere (Blackburn et al., 1970) that night micronekton does not show a clear maximum in these latitudes, although such a maximum might be expected, and zooplankton shows one. The data in this paper show a moderate maximum of skipjack forage, especially in day samples, although we do not know why day samples should give a different picture. Possibly the distribution of organisms is more even within the sampled water column by day than by night. If the organisms that occur at night were restricted to a thin layer of water (e.g., above the thermocline) and occurred there in patches, oblique hauls would sometimes under-sample them.

The forage maxima in the northwestern part of the EASTROPAC area occur in an area of relatively thick mixed layer (Wyrski, 1964) and low biological production (Blackburn, 1966). They represent occurrences of red crabs, *Pleuroncodes planipes*, that may have been transported from the upwelling off the coast of Baja California by the California Current (Longhurst, 1967; Longhurst and Seibert, 1971).

Regarding the relations of forage maxima and minima to physical features and processes in waters between 92° W and the coast, we refer the reader to our observations published elsewhere on maxima and minima of EASTROPAC micronekton (Blackburn, et al., 1970).

Three successful attempts have been made to demonstrate the abundance of skipjack in the EASTROPAC area since results described in this paper were first announced. Hida (1970) made a meridional crossing of the equator at about long 119° W in October 1969 between lat 6° S and 5° N. Skipjack were caught by trolling or live-bait fishing along most parts of the track, especially at three locations from lat 2° to 5° N where over 100 fish (including large ones) were caught with little effort at each location. Trolling also gave very promising results between lat 6° and 9° N at long 122°-125° W. A few fish were taken by live-bait fishing at about lat 4° S on long 119° W. Thus, skipjack were reasonably abundant at lat between 4° S and 9° N, a range which normally includes the northern equatorial forage maxi-

mum, part of the southern equatorial maximum, and part of the zonal maximum that occurs between lat 6° and 14° N. Williams (1971) reported on skipjack caught by trolling at various latitudes broadly along long 119° W in November and December 1970. The skipjack were most abundant in the region of the northern equatorial forage maximum, specifically at lat 1°-5° N. One of us (M. Blackburn) led a similar cruise broadly along long 119° W, in March and April 1971. On that occasion the abundance of trolled skipjack was highest at lat 9°-11° N, and next highest at lat 1°-3° N; skipjack forage was more abundant in both those zones than elsewhere. Further information about the cruises in 1970 and 1971 will be published later.

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Specification of Sea Surface Temperature Anomaly Patterns in the Eastern North Pacific¹

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(Manuscript received 31 January 1972, in revised form 14 April 1972)

ABSTRACT

Observed changes in sea surface temperature anomaly patterns on monthly and seasonal time scales are related to anomalous circulation patterns in the overlying atmosphere using data collected from the eastern North Pacific over a 10-year period (1961-70). Three monthly (November 1969, December 1969, January 1970) and four seasonal (fall 1969, winter 1969-70, spring 1970, summer 1970) case studies are described which show that the observed anomalous temperature changes can be explained quite well by relating them to anomalous heat transfer across the air-sea interface and heat advection by anomalous wind-driven ocean surface currents. These interactions are documented by charts showing the anomaly patterns of sea surface temperature change, sea level pressure, types of heat transfer across the air-sea interface, and wind drift currents. In addition, correlations computed between the anomaly patterns for each of the periods studied show that the interactions hypothesized have statistical significance. Although only seven case studies are described, the results are representative of those for most of the other months and seasons in the 10-year period.

An analysis of several years of data from Station PAPA (50N,145W), which included observed mixed layer depth values, indicates that between-year fluctuations in mixed layer depths can have a large effect in determining anomalous sea surface temperature changes, particularly when new seasonal thermoclines are forming. These effects should be included in any method used to specify (or predict) anomaly changes in order to avoid the relatively large errors that can occur from using long-term mean values.

1. Introduction

In a series of papers, Namias (1959, 1963, 1965, 1969, 1970, 1971) has shown that air-sea interaction processes can play an important role in determining the thermal structure and circulation characteristics of both ocean and atmosphere on monthly and seasonal time scales. Anomalous thermal or circulation patterns in either medium can create, amplify or destroy anomalous patterns in the other. These interactions occur on a contemporary or lag basis in time and over large (ocean-wide) spatial scales. The importance of understanding these interaction processes is now recognized as essential before meaningful long-range forecasting of atmospheric and oceanic properties can be made.

Most of Namias' studies presented qualitative and statistical results in defining the nature of air-sea coupling, although several of his reports (1959, 1963, 1965) and those of Eber (1961), Clark (1967) and Jacob (1967) described techniques that attempted to explain quantitatively the changes that occur in sea surface temperature anomaly patterns on monthly and seasonal time scales. The purpose of this paper is to show, by describing several case studies in both a qualitative and quantitative manner, that these observed anomalous changes can be related to well-known, large-scale, air-sea interaction processes.

It is important to note that this is an empirical study of these interaction processes. The methods used to describe and compute their effects are ones that consistently gave the best results in anomaly specification, with "best results" meaning the most significant positive pattern correlations and smallest rms errors between the computed and observed anomaly fields.

It is also noted that the specification procedure in this study is essentially the same as the one used by Clark (1967) to describe the anomalous fluctuations of sea surface temperature in the North Pacific throughout the 1951-57 period. The results reported here can be thought of as a verification of the ideas introduced in that study since they were obtained from a set of data that is independent of the set initially used to develop the specification procedure.

2. Development of the specification method

For a column of water of unit cross-sectional area and of depth D (z positive upward), the heat balance equation may be written as

$$\int_0^t \int_{-D}^0 \left(\rho C_p \frac{\partial T}{\partial t} \right) dz dt = \int_0^t \int_{-D}^0 Q_v dz dt + \int_0^t (Q + Q_D) dt, \quad (1)$$

¹ Presented at the Conference on the Interaction of the Sea and the Atmosphere, 1-3, December 1971, Ft. Lauderdale, Fla.

where T is the temperature of the water, Q the total heat transfer across the air-sea interface, Q_c the horizontal advection of heat into the column, and Q_D the vertical flux of heat into the column at depth $-D$. Since horizontal temperature gradients are small in most ocean areas, heat flux due to lateral diffusion is assumed to be negligible compared to the other heat exchange processes and is not included in (1). This equation expresses the relationship over the time interval t between the storage of heat in the column and the total exchange of heat energy between the column and its environment.

The differential form of (1) can be written as

$$\partial T / \partial t = -\mathbf{v} \cdot \nabla T + q, \quad (2)$$

where $-\mathbf{v} \cdot \nabla T = Q_c / (\rho C_p)$ and $q = Q / (\rho C_p \Delta z)$. The effects of Q_D are neglected because of a lack of adequate data to determine its importance in anomaly specification. However, order-of-magnitude estimates made from anomaly values of vertical velocity at the bottom of the Ekman layer and representative temperature lapse rates in the eastern North Pacific indicate that these effects are an order of magnitude less than the effects due to horizontal heat advection and heat transfer across the air-sea interface.

Following a method introduced by Arthur (1966) and modified by Clark (1968), let (2) be re-written as

$$D\theta / Dt = q, \quad (3)$$

where θ is the temperature of the upper mixed layer of the ocean and is assumed to be independent of depth, $\dot{\theta}$ is the rate of change of temperature of the layer due to non-advective processes, and $D\theta / Dt$ is the operator

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z}.$$

Throughout the rest of the paper, the term "sea surface temperature" will refer to the temperature θ of the upper mixed layer or quasi-isothermal layer above the seasonal thermocline.

Letting θ, u, v, w, q be expressed in the forms $\theta = \bar{\theta} + \theta'$, $u = \bar{u} + u'$, $v = \bar{v} + v'$, $w = \bar{w} + w'$, $q = \bar{q} + q'$, where the capital letters denote long-term averages of the quantities for a particular location and month and the primed terms individual monthly deviations from these averages, the equivalent form of (3) is

$$\begin{aligned} \frac{d(\bar{\theta} + \theta')}{dt} &= -(\bar{u} + u') \frac{\partial(\bar{\theta} + \theta')}{\partial x} - (\bar{v} + v') \frac{\partial(\bar{\theta} + \theta')}{\partial y} \\ &\quad - (\bar{w} + w') \frac{\partial(\bar{\theta} + \theta')}{\partial z} + (\bar{q} + q'). \quad (4) \end{aligned}$$

If a horizontal bar over a product of terms indicates that an average value of the product has been computed over all available data for a particular month, the

normal or long-term mean value of (4) becomes

$$\begin{aligned} \frac{\partial \bar{\theta}}{\partial t} &= -\left[\bar{u} \frac{\partial \bar{\theta}}{\partial x} + \bar{v} \frac{\partial \bar{\theta}}{\partial y} + \bar{w} \frac{\partial \bar{\theta}}{\partial z} \right] \\ &\quad - \left[\overline{u' \frac{\partial \theta'}{\partial x}} + \overline{v' \frac{\partial \theta'}{\partial y}} + \overline{w' \frac{\partial \theta'}{\partial z}} \right] + \bar{q}. \quad (5) \end{aligned}$$

Subtracting (5) from (4) and integrating the result from time t_1 to t_2 (neglecting the effects of vertical motion), the following equation relates the change in sea surface temperature anomaly between times t_1 and t_2 to the effects of horizontal advection of sea surface temperature and non-advective heat transfer during this period:

$$\begin{aligned} \theta'(t_2) - \theta'(t_1) &= - \int_{t_1}^{t_2} [\bar{u} \partial \theta' / \partial x + \bar{v} \partial \theta' / \partial y] dt \quad (a) \\ &\quad - \int_{t_1}^{t_2} [u' \partial \theta' / \partial x + v' \partial \theta' / \partial y] dt \quad (b) \\ &\quad - \int_{t_1}^{t_2} [u' \partial \bar{\theta} / \partial x + v' \partial \bar{\theta} / \partial y] dt \quad (c) \\ &\quad + \int_{t_1}^{t_2} [\overline{u' \partial \theta' / \partial x} + \overline{v' \partial \theta' / \partial y}] dt + \int_{t_1}^{t_2} q' dt. \quad (d) \quad (e) \quad (6) \end{aligned}$$

Integral (a) in (6) represents the change in sea surface temperature anomaly (or anomalous change in sea surface temperature) over the period t_1 to t_2 due to the interaction between the mean surface current and the anomalous temperature gradients; integral (b) represents the interaction between the current and gradient anomalies; integral (c) represents the interaction between the current anomalies and the mean temperature gradient; integral (d) represents an effect involving possible correlations between the current and gradient anomalies; and integral (e) represents the effect of anomalous heat transfer across the air-sea interface.

Integral (c) in (6) can also be identified with the procedure introduced by Namias (1965) and used by Jacob (1967) to specify the change in sea surface temperature anomalies over an interval $t_2 - t_1$ of one month. Clark (1968) evaluated the relative magnitudes of the first four integrals in (6) using seven years (1951-57) of monthly averaged data over the North Pacific from 20 to 60N. His results showed that the contribution of integral (c) to (6) predominates between 30-45N, and it is in this region that Namias and Jacob obtained their best results. In higher or lower latitudes, integrals (a) and (b) become important, while integral (d) involving

the correlation terms is small relative to the others and may be neglected.

The computational methods used in the present study to specify changes in θ' implicitly involve all five integrals in (6), thus including the effect of heat transfer across the air-sea interface [the integral (e)].

3. Heat transfer processes and data used in their computation

a. Formulation of the heat transfer equations

The total heat transfer across the air-sea interface Q (positive when the ocean surface layer is gaining heat) may be written as the downward flux of solar radiation Q_i minus the sum of the upward flux of longwave or back radiation Q_b , evaporative or latent heat transfer Q_e , and conductive or sensible heat transfer Q_s , or

$$Q = Q_i - (Q_b + Q_e + Q_s). \quad (7)$$

The terms on the right side of (7) are functions of time, cloud cover over the ocean surface, wind speed over the surface, and the air-sea difference of temperature and vapor pressure. The formulas used in determining the values of these terms are those given in Johnson *et al.* (1965).

The horizontal advection of heat Q_e at depth $-z$ may be written as

$$Q_e = -\rho C_p (\mathbf{v}_e \cdot \nabla T), \quad (8)$$

where ρ is the density of sea water, C_p the specific heat of sea water at constant pressure, $\mathbf{v}_e$ the horizontal current velocity at depth $-z$, and ∇T the horizontal gradient of temperature at the same depth.

The results in the empirical studies of Namias (1959, 1965), Clark (1967) and Jacob (1967) indicate that the best method of specifying anomalous changes in sea surface temperature from horizontal advective processes is to use an expression first proposed by Ekman for the magnitude of the surface current velocity $\mathbf{v}_e$, i.e.,

$$v/w = 0.0127 / (\sin \phi)^{1/2}, \quad (9)$$

where v is the magnitude of the surface current, w the magnitude of the geostrophic wind, and ϕ the latitude value at a computational gridpoint. It is assumed in this method that winds near the ocean surface are capable of driving a surface layer of nearly isothermal water at some angle to the direction of wind flow.

Values of the average speed of the upper wind-mixed layer of the ocean were also computed from surface wind stress data using the equations that describe Ekman transport. The results were then used in conjunction with horizontal temperature gradients to obtain estimates of anomalous temperature changes due to horizontal heat advection. However, no consistent, significant correlations were found between the computed and observed anomalous change fields.

For the isothermal layer, (8) becomes

$$Q_e = -\rho C_p (u_e \theta_\lambda + v_e \theta_\phi), \quad (10)$$

where u_e and v_e are the east-west and north-south components of the surface current, and θ_λ and θ_ϕ are the east-west and north-south components of the horizontal temperature gradient of the isothermal layer.

From (9) the surface current components can be written as

$$u_e = 0.0127 (\sin \phi)^{1/2} (u_g \cos \alpha + v_g \sin \alpha), \quad (11a)$$

$$v_e = 0.0127 (\sin \phi)^{1/2} (v_g \cos \alpha - u_g \sin \alpha), \quad (11b)$$

where u_g and v_g are the east-west and north-south components of the geostrophic wind, and α is the angle between the geostrophic wind and the ocean surface current directions.

In computing u_e and v_e monthly averaged sea-level pressures and finite-difference approximations to the geostrophic wind equations in spherical coordinates were used. The horizontal gradients of surface layer temperature were computed from finite-difference approximations to the gradient relationships in spherical coordinates, i.e., from

$$\theta_\lambda = (1/R \cos \phi) (\partial \theta / \partial \lambda) \approx (1/R \cos \phi) (\Delta \theta / \Delta \lambda), \quad (12a)$$

$$\theta_\phi = (1/R) (\partial \theta / \partial \phi) \approx (1/R) (\Delta \theta / \Delta \phi), \quad (12b)$$

where R is the earth's radius, and λ and ϕ denote longitude and latitude in radians. The grid spacing was 5° , so that $\Delta \lambda$ and $\Delta \phi$ were 10° or $(\pi/18)$ rad.

There has been a great deal of speculation as to what value should be used for the angle α between the geostrophic wind and the ocean surface current. Namias (1959, 1965), Jacob (1967) and Clark (1967) used 45° in their computations. However, in this study when anomalous temperature changes were computed from (11) and (12) using several values for α between -45° and $+45^\circ$ and the results compared with observed values, significantly better correlations between the two were obtained when the surface current was assumed to flow in the same direction as the geostrophic wind, i.e., α was equal to 0° . This result may be explained if the assumption is made that the wind at the ocean surface is nearly the same angle to the *left* of the geostrophic wind as the ocean surface current is to the *right* of the surface wind. The surface wind drift current would then flow in a direction that is almost parallel to that of the geostrophic wind.

b. Monthly averaged data

The marine weather observations used in this study have been collected and processed at the National Marine Fisheries Service's La Jolla Laboratory since early 1960. Monthly averages of these observations taken over the eastern North Pacific were computed by 5° latitude-longitude sections and used to determine

monthly averaged values of Q_i , Q_b , Q_e , Q_s and Q_v . A 10-year mean of each variable was computed for each 5° section and month, yielding 93 grid-point values for each variable and each month. The grid extended from 20° – 55° N and westward from the coast to 180° W. Departures of the monthly averages from the 10-year means (anomalies) were then computed.

A monthly averaged value for any quantity V is written as

$$V = \bar{V} + V', \quad (13)$$

where V is the monthly averaged value, $\bar{V}$ the 10-year mean value, and V' the monthly departure from the mean value or anomaly. This notation will be used throughout the paper to denote long-term means and anomalies unless otherwise explained.

The accuracy of the exchange formulas in determining the transfer of heat depends upon the validity of the assumptions underlying the theory, the accuracy of the observational data, and the manner in which the formulas are used to calculate the heat transfer. Since the formulas are nonlinear, the use of monthly mean data instead of daily or hourly values could lead to errors.

Since monthly averaged variables were the only ones

available over a large area and a sufficiently long time period, they were used in this study to compute the heat transfer values. However, Clark's (1967) calculations with daily averaged data from two weather ships in the North Pacific and Kraus and Morrison's (1966) work using data from weather ships stationed in the North Atlantic indicate that the errors involved in using this procedure are acceptable in studying large-scale, air-sea interaction processes.

Eq. (10), which is used to determine heat transfer by horizontal advection, is also nonlinear in nature, and the use of monthly mean data could again cause errors. Nonetheless, monthly averaged values were used in this study, and the results obtained and described in the following sections indicate that this data base is sufficient to show some of the ways in which advective processes affect anomalous changes in large-scale, sea surface temperature patterns.

c. Seasonally averaged data

In addition to the monthly averaged values, seasonal averages of the marine weather observations were computed by 5° latitude-longitude sections. These results were used to determine seasonal averages, 10-year mean

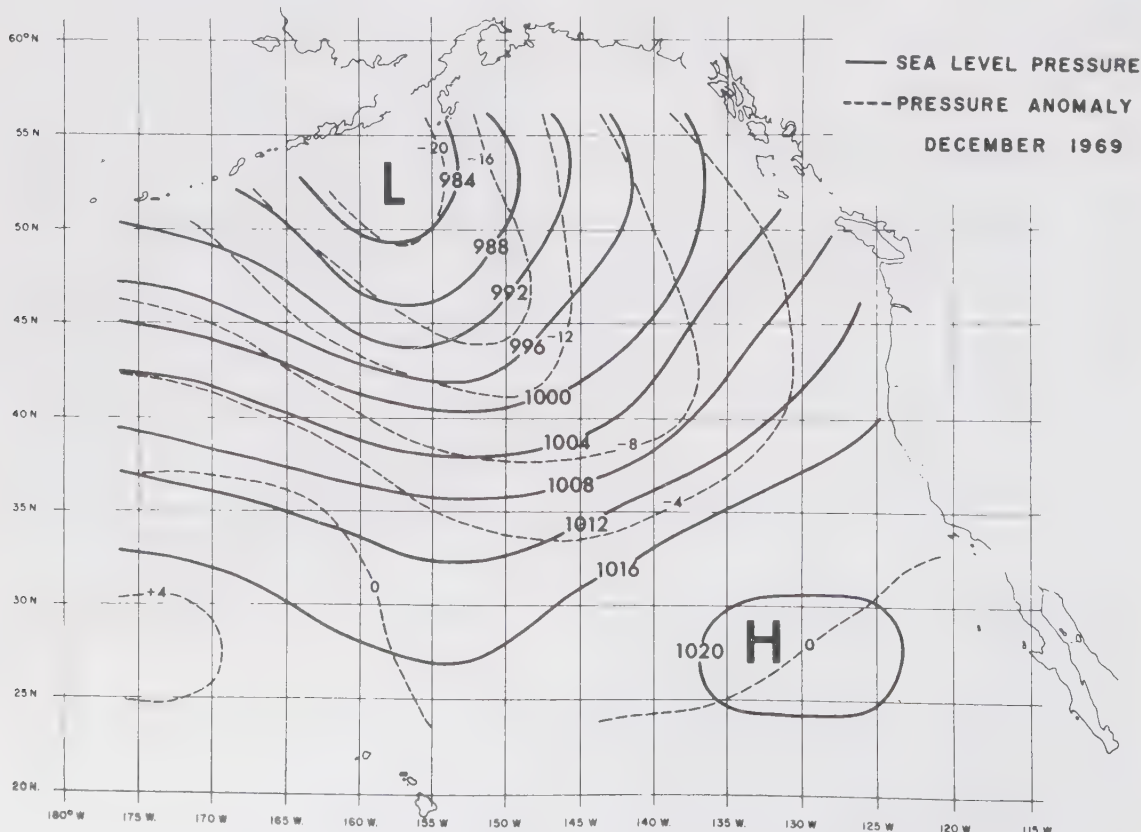


FIG. 1. Sea level isobars and anomaly isopleths (both in mb) for December 1969.

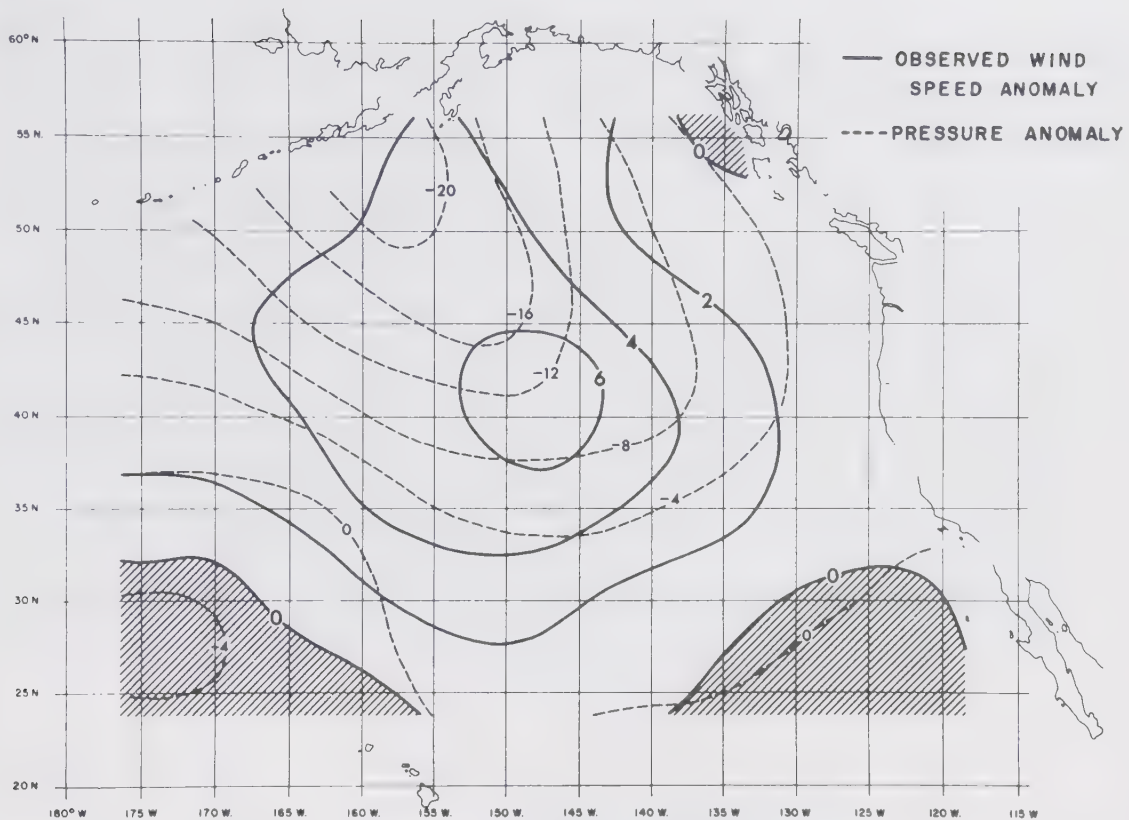


FIG. 2. Isopleths of observed wind speed anomaly (kt) and isopleths of sea level pressure anomaly (mb) for December 1969. Slant-shaded areas show regions of negative wind anomaly.

values, and seasonal anomalies for the same heat transfer terms that were computed using the monthly averaged variables. The 12 months were divided into four seasons, winter (December, January and February), spring (March, April and May), summer (June, July and August), and fall (September, October and November).

The discussion of inaccuracies caused by averaging procedures for the monthly averaged data also applies to the seasonally averaged values. In fact, the effects may be even more pronounced since longer time sequences are involved, at times, effectively masking important shorter term events. However, the high serial correlation found in sea surface temperature data (Namias, 1970) would seem to imply that seasonal means are quite indicative of the summation of daily effects.

4. Representative anomaly patterns of heat transfer processes

Fig. 1 shows the isobars of average sea level pressure (SLP) and the pressure anomaly pattern over the eastern North Pacific (ENP) for December 1969. The

negative departure of 20 mb south of the Alaskan Peninsula represents about three standard deviations from the 10-year mean and indicates the very strong cyclonic activity that occurred over the entire North Pacific during the month. A striking feature of the weather pattern over the ENP is its consistency throughout the month, with a negative 700-mb height anomaly of about 250 m (over three standard deviations from the mean) centered between 40–50°N and 140–160°W. The anomaly retained its intensity and configuration until the last week in December when it weakened and spread westward; however, the central region still had departures of almost two standard deviations from the mean (Posey, 1970).

The SLP anomaly pattern in Fig. 1 also shows the ways in which the anomalous atmospheric circulation during a month determines the general nature of the Q and temperature advection (TADV) anomaly patterns (Figs. 4 and 5). The orientation of the anomalous isobars indicates that cold, dry air moved into the eastern North Pacific from the northwest, causing increased evaporation and anomalous cooling of the ocean surface layer. These northwest winds also caused

anomalous cooling of the surface layer west of 150W through temperature advection. On the other hand, where the orientation of the isobars shows anomalous flow of warm, moist air from the south or southwest, the negative anomalies of evaporation are reduced in magnitude; the temperature advection anomalies are positive due to warmer water from the south having been transported northward by anomalous wind drift currents.

Fig. 2 shows the isotachs of anomalous observed (not geostrophic) surface wind speed along with the anomalous isobars. This superimposition of anomaly patterns points out several interesting relationships: 1) the observed wind speed anomalies (OBSW') are quite spatially coherent over the entire ENP; 2) the anomalies are positive over almost the entire region, indicating that the strong cyclonic activity during the month caused stronger than normal winds; and 3) the highest anomalous winds occurred in the same areas as the tightest anomalous pressure gradients, with maximum values (>6 kt) associated with the region of maximum atmospheric instability due to large air mass contrasts.

Since evaporative heat transfer Q_e is dependent upon wind speed, the large values of OBSW' between lati-

tudes 30 and 40N and longitudes 135 and 150W explain the large negative values of Q_e' in this area (Fig. 3), even though the anomalous winds are from the south or southwest.

The anomaly pattern of total heat transfer across the air-sea interface is shown in Fig. 4. There is a strong resemblance between this pattern and that in Fig. 3, indicating the strong influence of anomalous Q_e on Q (pattern correlation between the values of Q' and Q_e' is 0.95, or the two patterns have 91% of their variances in common). This relationship is typical of those found in most late fall and winter months.

The positive Q' values in the eastern Gulf of Alaska are due to a combination of less than normal evaporative cooling and longwave back radiation Q_b' . The latter effect is related to above-normal cloud cover in this region associated with the frequent passage of storm systems. North of Hawaii, between 33 and 37N, the negative anomaly of $150 \text{ cal cm}^{-2} \text{ day}^{-1}$ represents an approximate change of -0.50°C in the temperature of the ocean surface layer during the month.

The heat transfer due to horizontal advective processes is given by (10). If this equation is divided by ρC_p , the result expresses the change in sea surface

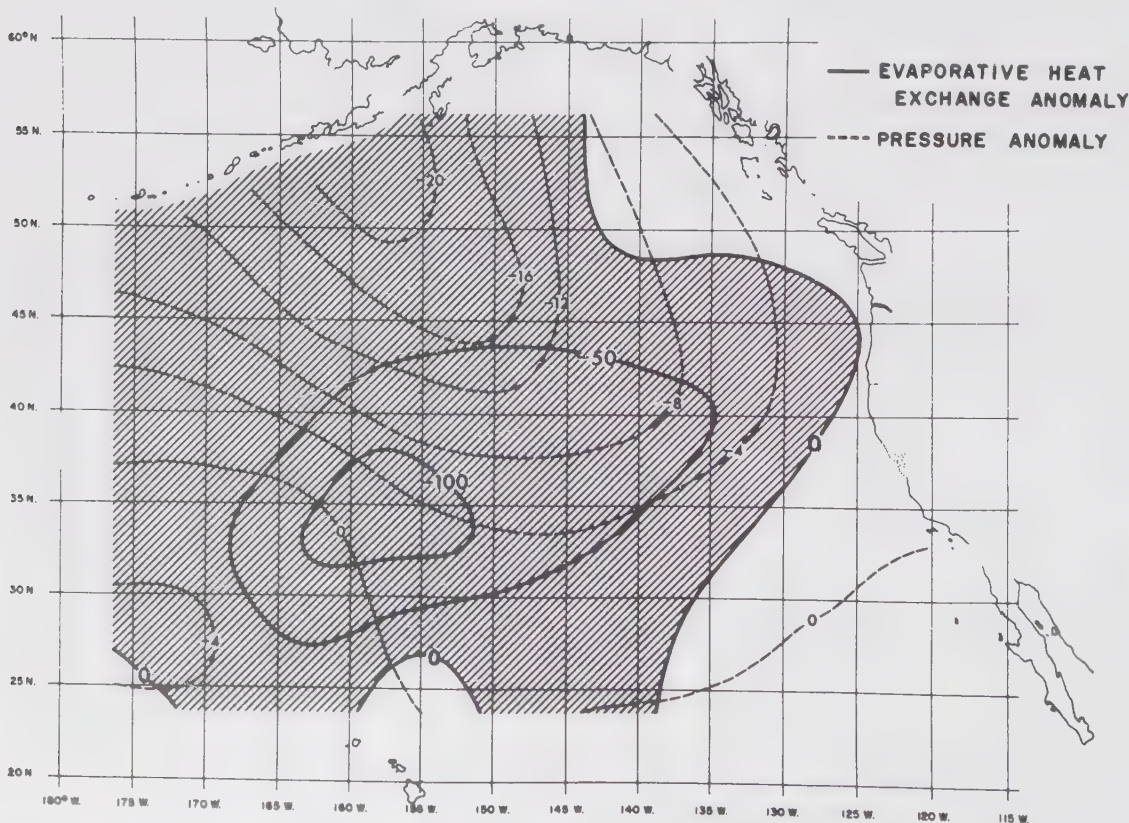


FIG. 3. Isopleths of evaporative heat exchange Q_e anomaly ($\text{cal cm}^{-2} \text{ day}^{-1}$) and isopleths of sea level pressure anomaly (mb) for December 1969. Slant-shaded area shows region of negative Q_e anomaly.

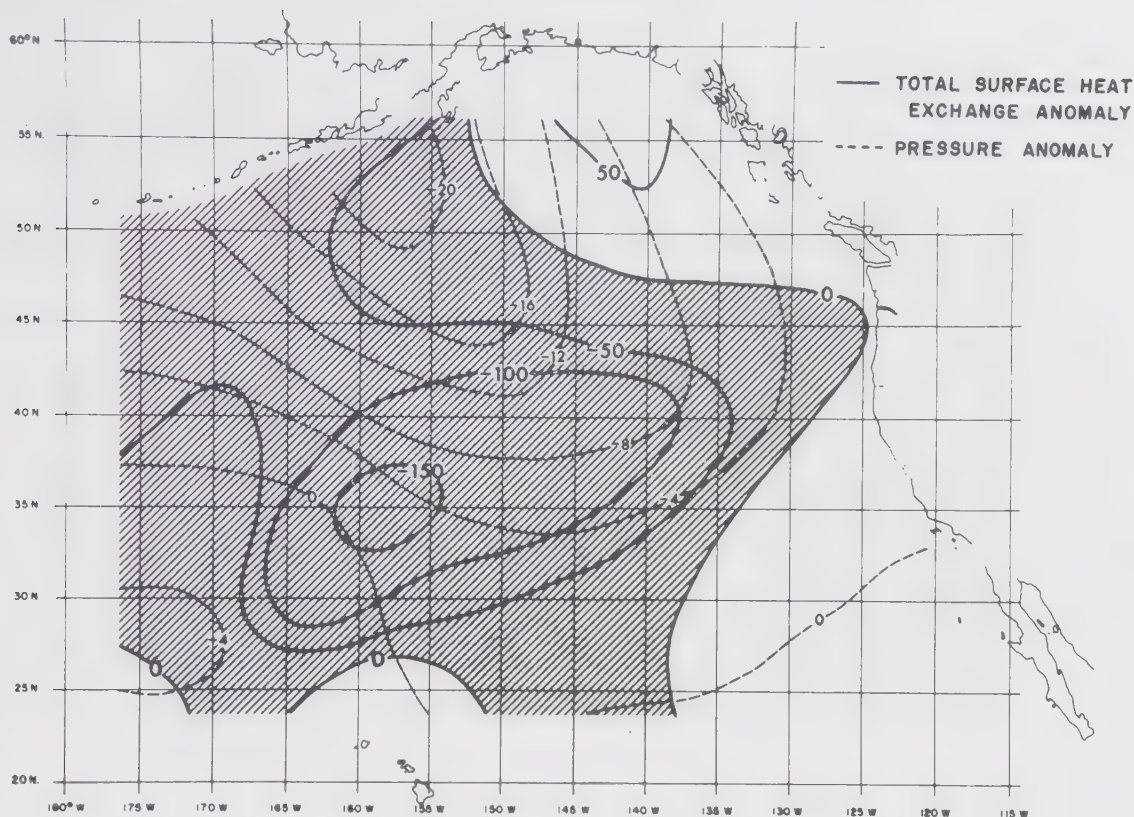


FIG. 4. Isopleths of total surface heat exchange Q anomaly ($\text{cal cm}^{-2} \text{ day}^{-1}$) and isopleths of sea level pressure anomaly (mb) for December 1969. Slant-shaded area shows region of negative Q anomaly.

temperature due to horizontal wind drift currents (TADV; anomalous value given by TADV'). The pattern of TADV' with the anomalous isobars superimposed for December 1969 is shown in Fig. 5. The results are as expected: negative anomalies in areas where the isobar orientation is from northwest to southeast, and positive anomalies in areas where the orientation ranges between southwest to northeast and southeast to northwest. Large positive and negative values of TADV' occur in regions of large OBSW', and the maximum value (about 0.75°C per month) occurs where OBSW' is high, the surface isotherms run nearly west to east, and the anomalous isobars show anomalous winds from the south.

5. Relationships between anomalous changes in sea surface temperature patterns and heat transfer processes

a. Results using a monthly time scale

Three months, November and December, 1969, and January 1970, were chosen from the 10-year record of data to illustrate the types of large-scale air-sea interaction processes that occur and their effects on the

thermal characteristics of the upper mixed layer of the ocean. Although the results are shown for only three months, and those for only one month, December 1969, are described in detail, they are representative of most of the other months in the 10-year period.

In Section 2, changes in sea surface temperature anomalies were related to anomalies of temperature advection and non-advective heat transfer. If the long-term mean of (3),

$$\overline{(\partial\theta/\partial t)} = (-\mathbf{v}_e \cdot \nabla\theta) + \bar{q}, \quad (14)$$

is subtracted from (3), those results can be represented by

$$(\partial\theta'/\partial t)' = (-\mathbf{v}_e \cdot \nabla\theta)' + q'. \quad (15)$$

The term on the left side of (15) represents the anomalous time-rate-of-change of sea surface temperature θ at some location in the ocean and is affected by anomalous horizontal advective processes $(-\mathbf{v}_e \cdot \nabla\theta)'$ or TADV' and non-advective heat flux across the air-sea interface.

Since $q = Q/\rho C_p D$, values for q' in (15) can be determined from the values of Q' computed from (7). In converting the Q' values into anomalous temperature changes q' of the ocean surface layer, the assumption

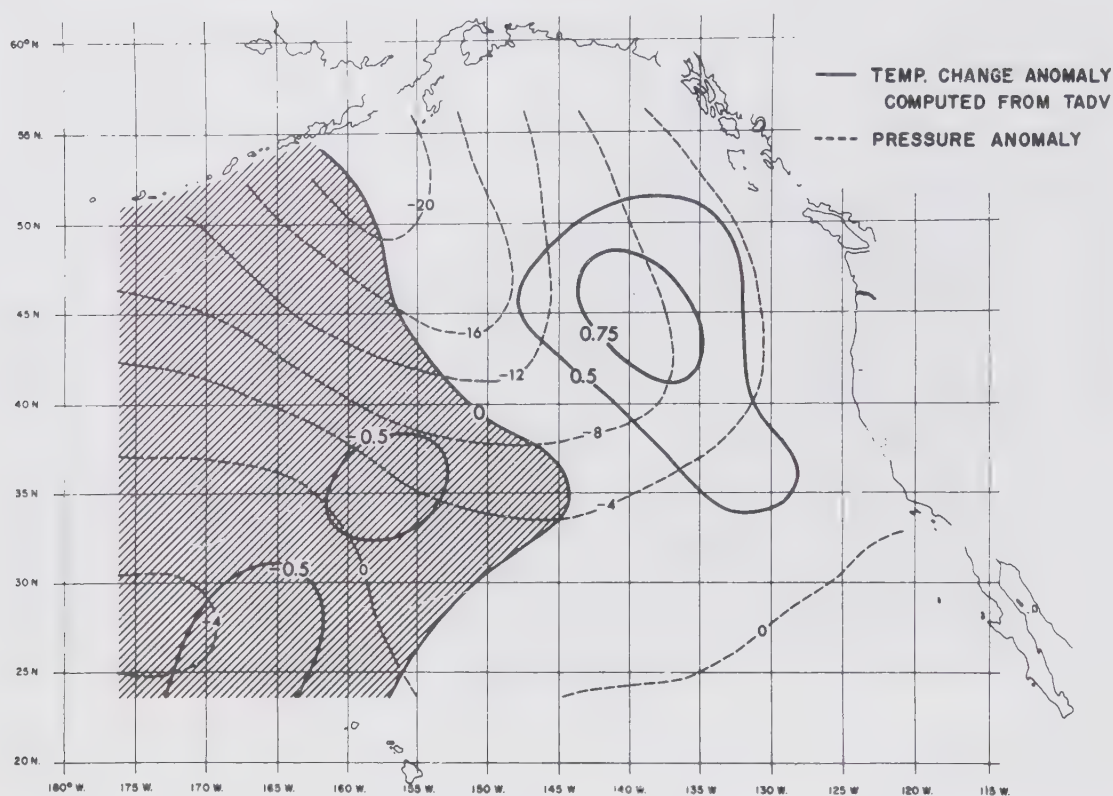


FIG. 5. Isopleths of sea surface temperature change anomaly ($^{\circ}\text{C}$) computed from horizontal temperature advection TADV and isopleths of sea level pressure anomaly (mb) for December 1969. Slant-shaded area shows region of negative TADV anomaly.

was made that the heat gained or lost is distributed evenly throughout a layer of depth D . The Q' values were then divided by $\rho C_p D$ to get the corresponding temperature change anomalies. Long-term mean values of the mixed layer depth D given by Pattullo and Cochrane (1951) were used in making these computations since observed values were not available. Errors resulting from the use of this procedure are discussed in Section 6.

Next, the q' values were added to those of TADV' and the results compared to the anomaly patterns of two finite-difference approximations to $\partial\theta/\partial t$. These approximations are described in the Appendix and are denoted by $\Delta\theta$ and $\Delta\theta'$. Figs. 6 and 7 show the anomaly patterns of $\Delta\theta'_{i,i-1}$ and $\Delta\theta'_{i+1,i-1}$ for December 1969, respectively. Although the two anomaly patterns differ in specifics, there is good correspondence in their pattern configurations.

Fig. 8 shows the anomaly pattern of TADV' + q' for December 1969. Visual comparison of the pattern in Fig. 8 with those in Figs. 6 and 7 shows that the anomalous temperature changes computed from anomalous advective and non-advective heat fluxes are often

twice the size of the estimated observed changes; however, their pattern configurations are quite similar.

In order to test the degree of similarity, linear correlations and rms differences were calculated between the values making up the patterns in Figs. 6–8. The results are shown in Table 1, with those for November 1969 and January 1970 included for comparison. These two months were different from December in that their anomalous atmospheric circulation patterns were not as consistent (Green, 1970; Wagner, 1970). Therefore, atmospheric events occurring on shorter time scales than 30 days probably had effects on the thermal characteristics of the ocean surface layer, and monthly averaged properties of the two media would not be expected to show a high degree of correlation.

The results show the highest pattern correlations and the smallest rms differences in December 1969. Depending on the scheme used to estimate $\partial\theta/\partial t$, the correlation coefficients are 0.81 (66% of variances in common) between $\Delta\theta'_{i,i-1}$ and TADV' + q' , and 0.66 (43% of variances in common) between $\Delta\theta'_{i+1,i-1}$ and TADV' + q' .

Both correlation coefficients greatly exceed the 1%

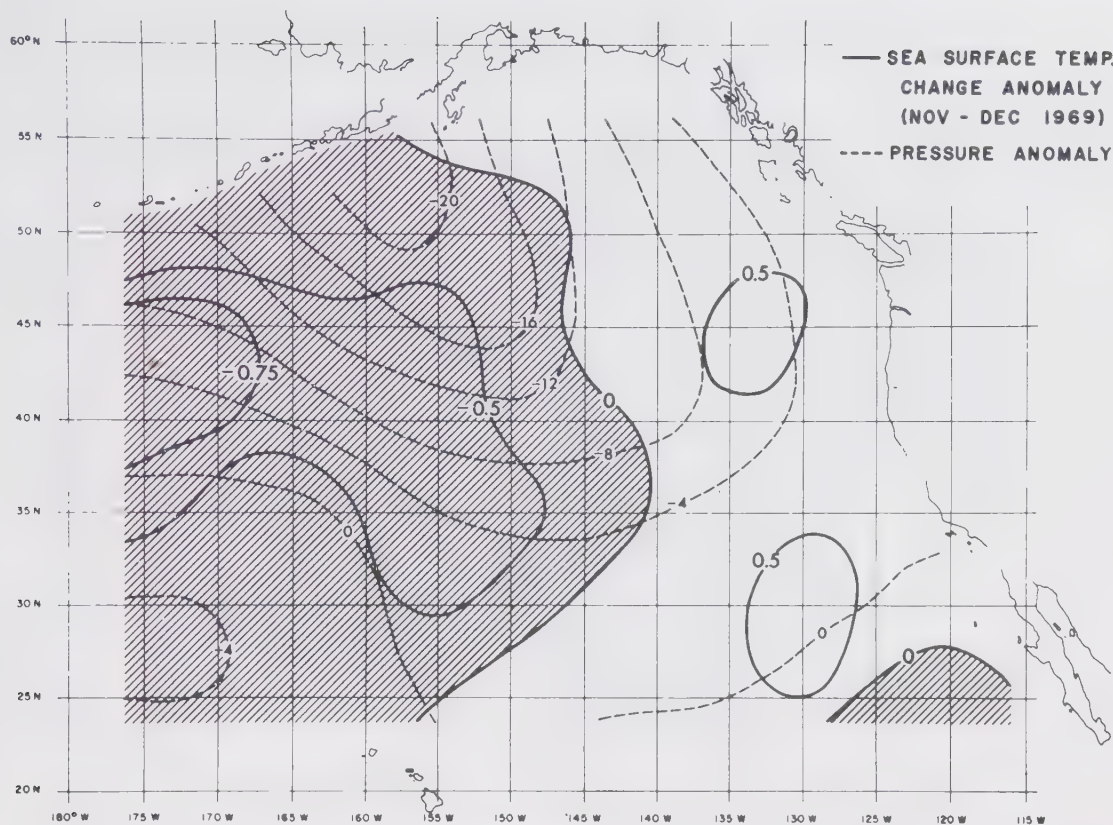


FIG. 6. Isopleths of observed sea surface temperature change anomaly ($^{\circ}\text{C}$) approximated using the backward finite-difference method and isopleths of sea level pressure anomaly (mb) for December 1969. Slant-shaded areas show regions of negative temperature change anomaly.

level of statistical significance (0.30) for 93 data points or 92 degrees of freedom. Since the values used in the correlations are not truly independent of each other, the 1% level should be higher than 0.30. However, positive correlations were consistently obtained using data for other months, and it is felt that the relationships indicated are real and not obtained by chance.

The correlations for November 1969 are lower than those for December 1969 but higher than those for January 1970. While all but two of the correlation coefficients equal or exceed the 1% (0.30) or the 5% (0.23) levels of statistical significance using the November 1969 results, none of them computed for January 1970 reach the 5% level. Descriptions of the atmospheric circulation patterns for the two months (Green, 1970; Wagner, 1970) show that the anomalous activity in November 1969 was more intense and consistent than that in January 1970.

For all three months, TADV' correlated better with $\Delta\theta'_{i, i-1}$, and q' correlated better with $\Delta\theta'_{i+1, i-1}$. Using this as a guide, it is seen from Table 1 that advective processes probably had a greater influence than non-

advective processes in determining the anomalous temperature changes in December 1969, while the reverse appears to be true in November 1969 and January 1970.

b. Results using a seasonal time scale

Table 2 shows the results of computing the same type of correlations discussed in the previous section except that seasonal rather than monthly data were used. The time periods chosen for study were fall 1969 (September, October and November, 1969), winter 1969–70 (December, 1969, January and February, 1970), spring 1970 (March, April and May, 1970), and summer 1970 (June, July and August, 1970). Again, as for the monthly data, the results are typical of the other seasons in the 10-year data record.

Of the four seasons, winter 1969–70 and spring 1970 show the highest correlations and the smallest rms differences. The correlations for summer 1970 are also high and represent the dominant influence of non-advective processes during this season. The correlations for fall 1969 are all quite low and reflect one or any combination of the following: 1) use of long-term mean

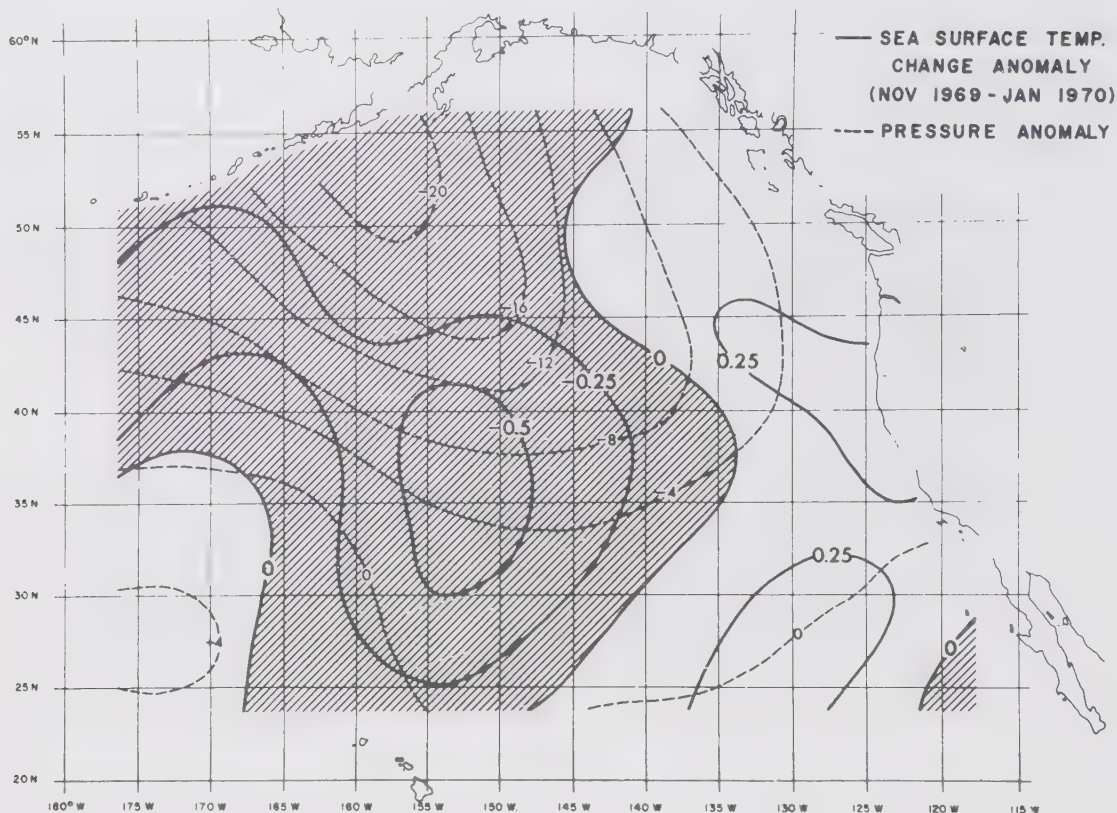


FIG. 7. Isopleths of observed sea surface temperature change anomaly ($^{\circ}\text{C}$) approximated using the centered finite-difference method and isopleths of sea level pressure anomaly (mb) for December 1969. Slant-shaded areas show regions of negative temperature change anomaly.

values for mixed layer depths; 2) seasons before and after biasing the estimations of $\partial\theta/\partial t$; and 3) exclusion of effects of other processes such as heat transfer across the seasonal thermocline. Correlations were computed using data for fall 1970 with essentially the same results.

From these results, it appears that advective heat transfer processes have a greater effect in determining anomalous sea surface temperature changes than non-advective processes in winter and spring, while the latter have a greater effect in summer and fall.

Comparisons were also made between the total heat transfer Q across the air-sea interface and the different processes contributing to the anomalous variations in Q . The pattern correlation coefficients in Table 3 indicate that: 1) during fall 1969, winter 1969-70 and spring 1970, anomalous changes in the evaporative heat transfer Q_e are mainly responsible for corresponding changes in Q ; 2) during summer 1970 the Q_e anomaly pattern is also highly correlated with the Q pattern, however, during this season anomalies in the incoming radiation Q_i play a major role in determining the Q anomaly pattern; and 3) the Q anomaly patterns are negatively correlated with those of cloud cover in

spring and summer 1970, reflecting the dependence of Q on Q_i during these seasons since increased cloud cover causes a decrease in radiation reaching the ocean surface. The correlation between the Q_e and observed wind speed anomaly patterns is smaller in summer 1970 than in the other three seasons, indicating that air-sea vapor pressure differences played a stronger role in determining evaporation during this period. These results are similar to those obtained for other years in the 1961-70 period.

6. Discrepancies between observed and computed anomalous sea surface temperature changes

In determining the anomalous changes in sea surface temperature patterns from the anomaly patterns of the total heat transfer across the air-sea interface or non-advective processes q , mean values of the mixed layer depth were used because observed monthly averaged values were not available over the entire eastern North Pacific. Since relatively large fluctuations of the monthly averaged values do occur between the same months of different years, the use of long-term mean values will

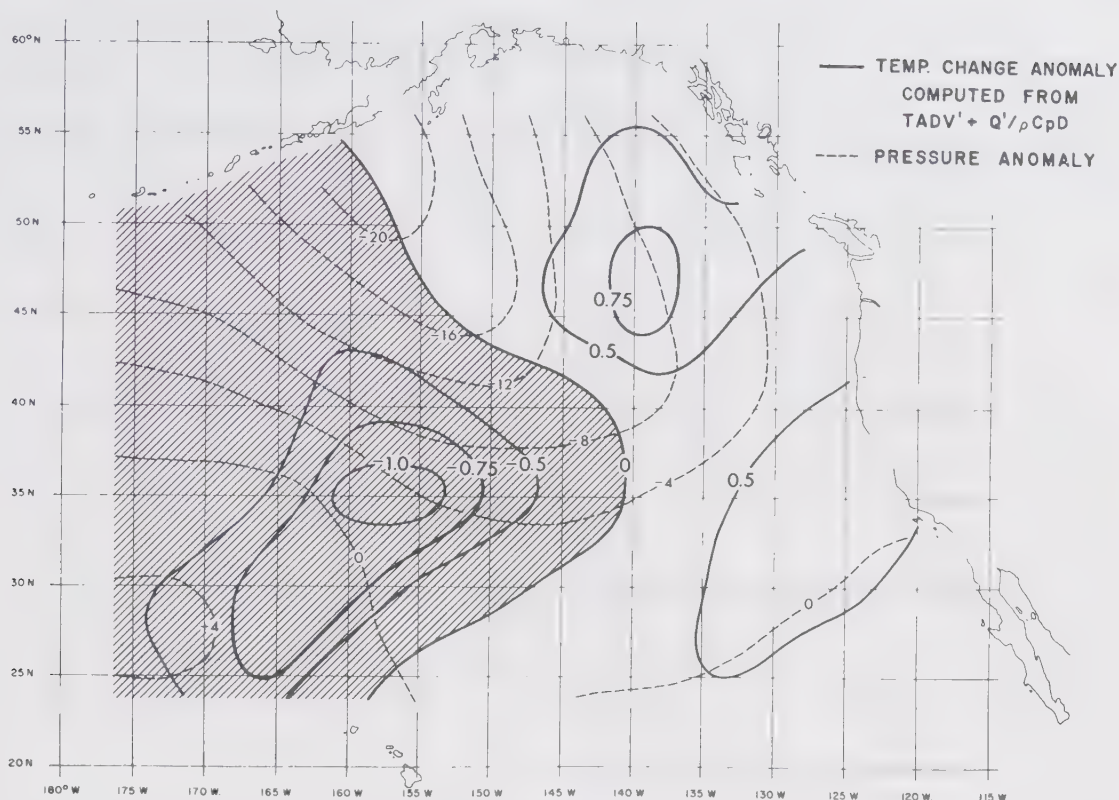


FIG. 8. Isopleths of sea surface temperature change anomaly ($^{\circ}\text{C}$) computed from temperature advection TADV and total surface heat transfer $Q/(\rho C_p D)$ and isopleths of sea level pressure anomaly (mb) for December 1969. Slant-shaded area shows region of negative TADV + $Q/(\rho C_p D)$ anomaly.

cause errors in specifying anomalous temperature changes in certain areas and at certain times of the year. The effects of using the long-term mean values instead of monthly averaged observed values can be demonstrated by the following:

Using (3) in the form

$$\partial\theta/\partial t = -\mathbf{v}_e \cdot \nabla\theta + Q/(\rho C_p D), \quad (16)$$

and letting $Q = \bar{Q} + Q'$ and $D = \bar{D} + D'$ where the bar denotes a long-term mean value and the prime a deviation from the mean value or anomaly, the second term on the right side of (16) can be written as

$$\begin{aligned} \frac{Q}{\rho C_p D} &= \frac{\bar{Q} + Q'}{\rho C_p (\bar{D} + D')} \\ &= \frac{(\bar{Q} + Q')}{\rho C_p \bar{D}} \left[1 - \frac{D'}{\bar{D}} + \left(\frac{D'}{\bar{D}} \right)^2 - \dots \right]. \end{aligned} \quad (17)$$

Assuming $D' < \bar{D}$ so that terms of second order or higher inside the brackets on the right side of (17) can

be neglected, then

$$\frac{Q}{\rho C_p D} \approx \frac{(\bar{Q} + Q')}{\rho C_p \bar{D}} \left[1 - \frac{D'}{\bar{D}} \right], \quad (18)$$

and

$$\left(\frac{Q}{\rho C_p D} \right)' \approx \frac{\bar{Q}}{\rho C_p \bar{D}} - \frac{D' \bar{Q}'}{\rho C_p \bar{D}^2}. \quad (19)$$

Since

$$\left(\frac{Q}{\rho C_p D} \right)' = \frac{Q}{\rho C_p D} - \left(\frac{Q}{\rho C_p D} \right), \quad (20)$$

substituting (18) and (19) into (20) and rearranging terms gives

$$\left(\frac{Q}{\rho C_p D} \right)' \approx \frac{Q'}{\rho C_p \bar{D}} - \frac{1}{\rho C_p \bar{D}} \left[\frac{D'}{\bar{D}} (\bar{Q} + Q') - \frac{D' Q'}{\bar{D}} \right]. \quad (21)$$

The left side of (21) denotes the anomalous temperature change due to nonadvective processes and is approximated by the sum of the three terms on the right side; the first term can be identified with the one

TABLE 1. Pattern correlation coefficients and rms differences between observed anomalous sea surface temperature changes and those computed from the effects of wind-driven ocean-surface currents (TADV'), heat transfer across the air-sea interface ($Q'/\rho C_p D$), and the sum of TADV' and $Q'/\rho C_p D$. The first group of figures for each month shows the results using the backward time-difference method to estimate the anomalous temperature changes, and the second group shows the results using the centered time-difference method.

		TADV'	$Q'/\rho C_p D$	TADV' + $Q'/\rho C_p D$
November 1969	$\Delta\theta'$	0.30 ¹	0.21	0.30
	$i, i-1$	(09) ²	(04)	(09)
		0.41 ³	0.37	0.53
	$\Delta\theta'$	0.19	0.70	0.44
December 1969	$i+1, i-1$	(04)	(50)	(19)
		0.38	0.17	0.48
	$\Delta\theta'$	0.77	0.54	0.81
	$i, i-1$	(60)	(29)	(66)
January 1970		0.32	0.36	0.30
	$\Delta\theta'$	0.48	0.71	0.66
	$i+1, i-1$	(23)	(50)	(43)
		0.37	0.18	0.38
January 1970	$\Delta\theta'$	0.12	0.03	0.12
	$i, i-1$	(01)	(00)	(02)
		0.46	0.36	0.52
	$\Delta\theta'$	0.11	0.20	0.20
	$i+1, i-1$	(01)	(04)	(04)
		0.36	0.20	0.43

¹ Pattern correlation coefficient.

² Reduction of variance.

³ Root-mean-square difference (°C).

used in this study to compute the anomalous temperature changes, the first term in the brackets represents the effect of fluctuations in mixed depth layer values,

TABLE 2. As in Table 1 except that the results are for seasons rather than months.

		TADV'	$Q'/\rho C_p D$	TADV' + $Q'/\rho C_p D$
Fall 1969	$\Delta\theta'$	0.30	-0.19	0.05
	$i, i-1$	(09)	(04)	(00)
		0.58	0.75	1.03
	$\Delta\theta'$	0.08	0.34	0.24
Winter 1969-70	$i+1, i-1$	(01)	(12)	(06)
		0.66	0.57	0.97
	$\Delta\theta'$	0.66	0.57	0.74
	$i, i-1$	(43)	(33)	(55)
Spring 1970		0.65	0.51	0.69
	$\Delta\theta'$	0.56	0.22	0.53
	$i+1, i-1$	(32)	(05)	(28)
		0.53	0.54	0.73
Summer 1970	$\Delta\theta'$	0.73	0.53	0.75
	$i, i-1$	(54)	(28)	(56)
		0.59	0.42	0.87
	$\Delta\theta'$	0.47	0.42	0.51
January 1970	$i+1, i-1$	(22)	(18)	(26)
		0.78	0.49	1.06
	$\Delta\theta'$	-0.08	0.54	0.44
	$i, i-1$	(01)	(30)	(19)
January 1970		0.81	0.67	0.80
	$\Delta\theta'$	0.28	0.54	0.61
	$i+1, i-1$	(08)	(29)	(37)
		0.46	0.66	0.73

TABLE 3. Pattern correlation coefficients and corresponding reduction of variances between heat transfer terms and observed variables.

		Total heat transfer Q'	Evaporative heat transfer Q_e'
Fall 1969	Q_e'	0.86	
		(74)	
	OBSW'	-0.56	-0.74
Winter 1969-70		(32)	(55)
	cc'	0.21	
		(04)	
Spring 1970	Q_e'	0.97	
		(95)	
	OBSW'	-0.48	-0.48
Summer 1970		(23)	(23)
	cc'	-0.07	
		(01)	
Spring 1970	Q_e'	0.89	
		(80)	
	OBSW'	-0.58	-0.56
Summer 1970		(34)	(32)
	cc'	-0.52	
		(27)	
Summer 1970	Q_e'	0.59	
		(35)	
	OBSW'	-0.44	-0.12
Summer 1970		(20)	(01)
	cc'	-0.56	
		(32)	
Summer 1970	Q_i'	0.50	
		(25)	

and the second term in the brackets represents the effect of possible correlations between anomalies in total heat transfer and mixed layer depth.

Order-of-magnitude specification errors resulting from the use of long-term mean values rather than monthly averaged observed values can be estimated by evaluating the relative magnitudes of the terms on the right side of (21) from data taken at Station PAPA between 1956 and 1963. The results of these computations are given in Table 4 (the terms were all multiplied by the common denominator $\rho C_p \bar{D}$ before the computations were made since only relative magnitudes are important). Values for each of the three terms were calculated for the four mid-season months, January, April, July and October, of five years for which all the necessary data were available.

In general, the values in Table 4 indicate that between-year mixed layer depth fluctuations have the greatest effect on the anomalous sea surface temperature changes during spring and summer, with the largest effects occurring when the new seasonal thermocline is developing. In fact, during April the term in (21) representing the effect of mixed layer depth anomalies on total heat transfer distribution is larger in four of the five years than the effect of total heat transfer anomalies. During July, it is larger for two of the five years, and on the average it is equally as important.

It appears that mixed layer depth anomalies have less effect on anomalous temperature changes during

TABLE 4. Relative magnitudes ($\text{cal cm}^{-2} \text{ day}^{-1}$) of the three terms on the right side of (21) using data from Station PAPA. The 1st column shows the total heat transfer anomalies Q' , the 2nd and 3rd columns show the effects of mixed layer depth anomalies on the total surface heat transfer distribution in the layer and percentage ratios of these effects to Q' , and the 4th and 5th columns show the effects of correlations between total heat transfer and mixed layer depth anomalies and the percentage ratios of these effects to Q' .

January					April						
Q'	$(D'/\bar{D}) \cdot (\bar{Q} + Q')$		$-\bar{D}'\bar{Q}'/\bar{D}$		Q'	$(D'/\bar{D}) \cdot (\bar{Q} + Q')$		$-\bar{D}'\bar{Q}'/\bar{D}$			
1956	-196	-48	24%	6.3	3%	1956	-8	-54	675%	-1.7	21%
1957	-45	13.3	30%	6.3	14%	1957	-5	4.4	88%	-1.7	3%
1961	41	0	0%	6.3	15%	1961	31	29.6	95%	-1.7	5%
1962	96	6	6%	6.3	6%	1962	-5	6.2	125%	-1.7	3%
1963	103	-1.7	2%	6.3	6%	1963	-14	20.6	147%	-1.7	12%
			12%		9%				226%		9%
July					October						
Q'	$(D'/\bar{D}) \cdot (\bar{Q} + Q')$		$-\bar{D}'\bar{Q}'/\bar{D}$		Q'	$(D'/\bar{D}) \cdot (\bar{Q} + Q')$		$-\bar{D}'\bar{Q}'/\bar{D}$			
1956	-44	-16.6	38%	10.1	22%	1956	-70	39.4	56%	-8.1	11%
1957	-80	44.4	56%	10.1	12%	1957	15	3.2	21%	-8.1	53%
1961	27	-71.2	264%	10.1	37%	1961	41	0	0%	-8.1	19%
1962	60	19.7	33%	10.1	16%	1962	82	-26.3	31%	-8.1	9%
1963	28	-34.2	122%	10.1	35%	1963	-68	-24.4	36%	-8.1	11%
			102%		24%				29%		21%

fall and winter, as indicated by the values shown for October and January. However, they cannot be overlooked since in some years these effects were 30–56% as large as those of total surface heat transfer anomalies. During October the average of the ratios is 29%, or the average effects of mixed layer depth anomalies are nearly one-third as large as the average effects of total heat transfer anomalies.

The values in Table 4 involving correlations between mixed layer depth and total heat transfer anomalies are smaller than those for either of the two considered separately. However, the correlation effects cannot necessarily be neglected in July and October since they average about one-fifth as large as the total surface heat transfer anomalies in these months, and are nearly as large as the effects of mixed layer depth anomalies in October.

7. Summary

In Section 2, a specification method was developed that relates the change in sea surface temperature anomalies between times t_1 and t_2 to anomalies of temperature advection and non-advective heat transfer across the air-sea interface integrated over the interval t_1 to t_2 .

In order to test the adequacy of the method, monthly and seasonally averaged marine weather observations from 1961–70 were used to compute monthly and seasonal anomalies of sea surface temperature change, temperature advection, and non-advective heat transfer over a network of grid points covering the eastern North Pacific. Descriptive and statistical comparisons were then made between observed changes in sea surface temperature anomaly patterns and those computed using the specification procedure. The results indicate

quite clearly that both advective and non-advective processes are important in determining the nature of temperature anomalies in the surface layer of the ocean. Their relative importance appears to depend upon the initial thermal state of the layer and the subsequent character of the overlying atmospheric circulation.

The highest correlations between observed and specified anomalous changes were obtained for periods when anomalous atmospheric activity over the eastern North Pacific was intense and quite persistent. Under these conditions, computed temperature changes are probably more representative of those that actually occur since errors resulting from the use of monthly or seasonally averaged data in the nonlinear transfer equations become less serious.

Comparisons between the observed and specified seasonal anomaly patterns indicate that temperature advection has a greater effect in determining anomalous sea surface temperature changes in winter and spring, while non-advective processes appear to have a greater effect in summer and fall.

In Section 6, a perturbation-type analysis of the non-advective heating expression $Q/(\rho C_p D)$ was made in order to estimate the effects of using long-term mean values of the mixed layer depth D instead of observed values in computing anomalous sea surface temperature patterns. In order to eliminate these errors and improve specification results, data on the vertical temperature structure of the ocean will have to be obtained so that mixed layer depths can be determined for time periods that correspond to those used in a particular specification method.

Finally, an important factor to keep in mind is that air-sea interaction processes do not conform to any standard time scales such as months, seasons, etc. In order to improve our knowledge of these processes, time

scales that represent the varying atmospheric circulation periods will have to be examined. The descriptions and statistics presented here only point out that known processes are having effects on large time and space scales, and no attempt has been made to explain all the features of these complete interactions.

Acknowledgments. I thank Mr. James A. Renner for his invaluable assistance in data preparation, computer programming, and initial drafting of the figures, Mr. Kenneth S. Raymond for the final drafting of the figures, and Miss Joanne Webber for typing the manuscript.

APPENDIX

Finite Difference Approximations

In order to test the validity of the relationship expressed by (15) and the assumptions made in determining the heat flux components, $\partial\theta/\partial t$ needs to be approximated by some finite difference scheme, $\partial\theta/\partial t \approx \Delta\theta/\Delta t$, where $\Delta\theta$ denotes the change in sea surface temperature over a time interval Δt . Since monthly averaged data were used to compute the terms on the right side of (15), $\Delta\theta/\Delta t$ should be determined from the temperature values at the beginning and end of each month. However, this information was not available, and it was necessary to approximate $\Delta\theta/\Delta t$ using the monthly averaged temperature values.

The first approximation method used is a "backward" finite-difference scheme in which $\Delta\theta/\Delta t$ is computed from the difference between the value of θ for the month over which the approximation is desired and the value of θ for the previous month. This scheme is represented by $\Delta\theta_{i, i-1}$ where i denotes the present month and $i-1$ denotes the previous month. Monthly averaged values, 10-year mean values, and monthly anomaly values were computed using the 120 months in the 10-year data record.

The other method used in approximating $\Delta\theta/\Delta t$ is a "centered" finite-difference scheme in which half the difference between the value of θ for the month subsequent to the one over which the approximation is desired and the value of θ for the previous month is computed. This scheme is represented by $\Delta\theta_{i+1, i-1}$ where $i+1$ denotes the subsequent month, and $i-1$ denotes the previous month. Again, monthly averaged

values, 10-year mean values, and monthly anomaly values were computed.

A major drawback in using either of these approximations is that the values obtained might be strongly biased by unusually anomalous events occurring in one of the months previous or subsequent to the one for which $\Delta\theta/\Delta t$ is needed.

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REMOVING PORPOISE FROM A TUNA PURSE SEINE

James Coe and George Sousa

Between 50 and 70% of the annual U.S. catch of yellowfin tuna in the eastern tropical Pacific comes from schools associated with porpoise (unpublished data, Inter-American Tropical Tuna Commission). Tuna primarily associate with two species, the so-called "spotters" and "spinners." At times, they may be found in the company of a third species, which fishermen call "whitebellies" (Perrin, 1968, 1969, 1970; Green, Perrin and Petrich, 1971). Once the seine has been set and pursed around a school of porpoise and the associated tuna, the problem arises of releasing the porpoise unharmed without losing the fish.

In the interest of disseminating information that will contribute to conservation of the porpoise stocks, this paper presents a detailed account of the equipment and methods used by one seiner that has attained a high degree of success in removing porpoise from its net.

VESSEL AND EQUIPMENT

The specifications of the vessel and its net skiff follow:

	Vessel	Net skiff
Length	165 ft (50.4 m)	31 ft (9.5 m)
Beam	34 ft (10.4 m)	18 ft (5.5 m)
Depth	17 ft (5.2 m)	5 ft (1.5 m)
Engine	2800 hp	250 hp
Hull	Steel	Steel
Year of construction	1970	1970
Brine well capacity	650 short tons	

The main purse winch on this vessel was a Marco model 1072 built by the Marco Corporation, Seattle, Washington. It was driven by a 333 hp Caterpillar diesel engine coupled to a Vickers hydraulic system providing 1500 psi at 70 gallons per minute. The Marco 42-inch

diameter power block was integrated into the same hydraulic system.

The Net

The net used by this seiner was hung 570 fathoms long and about 52 fathoms deep in 1970; since then, it has shrunk to approximately 540 fathoms by 48 fathoms. The basic construction was described by McNeely in 1961--with the exceptions that the net was nine strips deep, and the bunt sections at the bunt end and at the single cutting strip at half net were made with number 96 twine. This net lacked the Medina escape panel of 2-inch webbing to prevent porpoise entanglement, which is currently being adopted by many boats in the U.S. fleet.

METHODS

The technology of tuna purse seining in general and "porpoise-fishing" in particular has previously been described (Green, et al., 1971). The following pertains to details of operation that bear on efficiency in removing porpoise from the net alive.

When the porpoise school has been bunched as tightly as possible, and the school is stopped or running generally upwind, the set is made in a slightly cross and downwind direction. Setting in this manner keeps the wind on the stern port quarter of the vessel while the net is being pursed, and the net stays open nicely. Even with a fairly strong current, setting with the wind on the port side, combined with the pulling of the net skiff, will usually keep the boat from drifting into the net.

While the net is being pursed, there is a tendency for the slack corkline and webbing to wrap around the bow and stern of the boat. This forms bags or pockets where porpoise may become trapped. The bow bend pocket is eliminated as it forms by pulling three 40-

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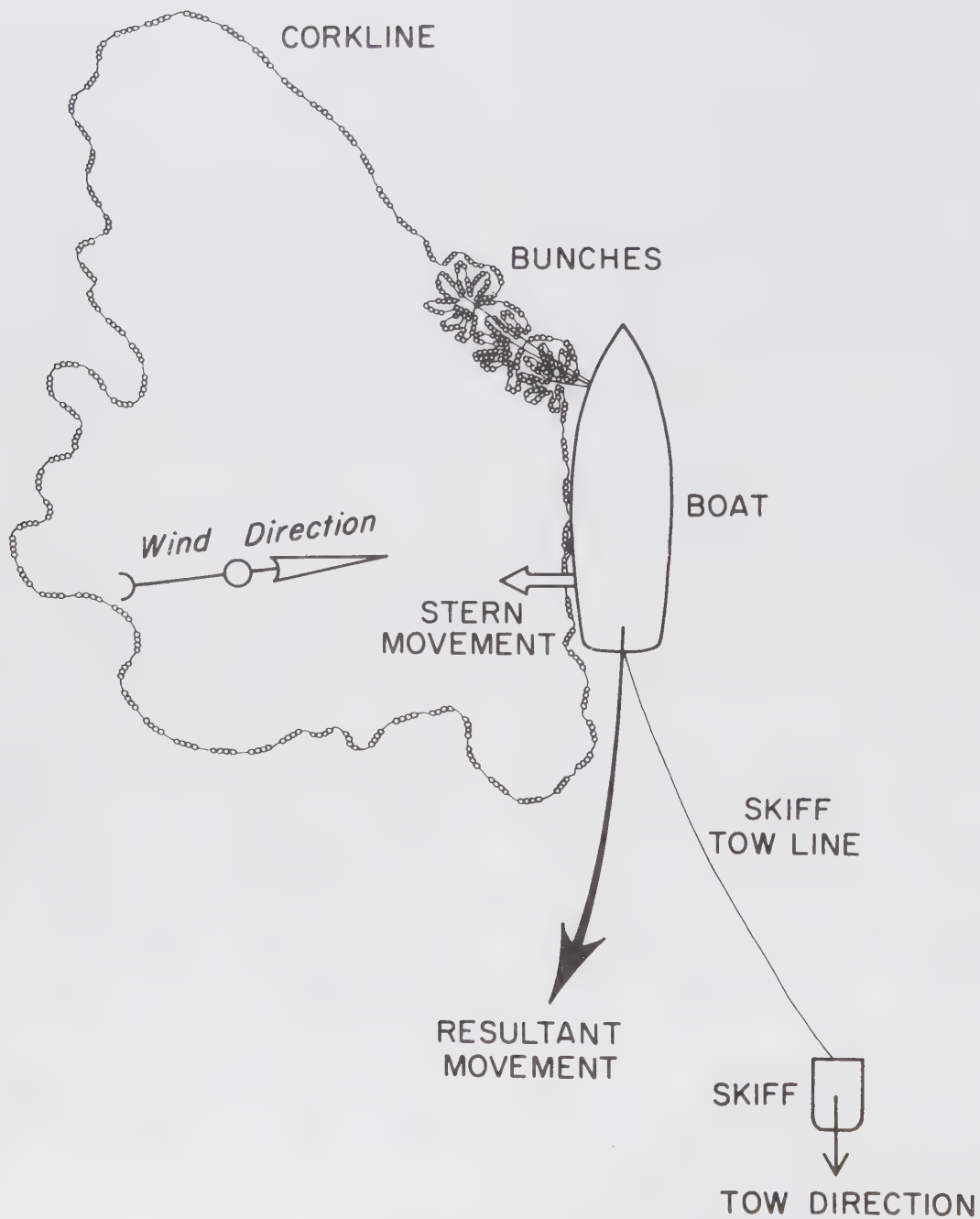


Fig. 1 Rolling net causes the stern of the boat to move into the net (double arrow) so that the skiff tows parallel to the axis of the boat, and the resulting movement is backward in a large clockwise semicircle (solid black arrow).

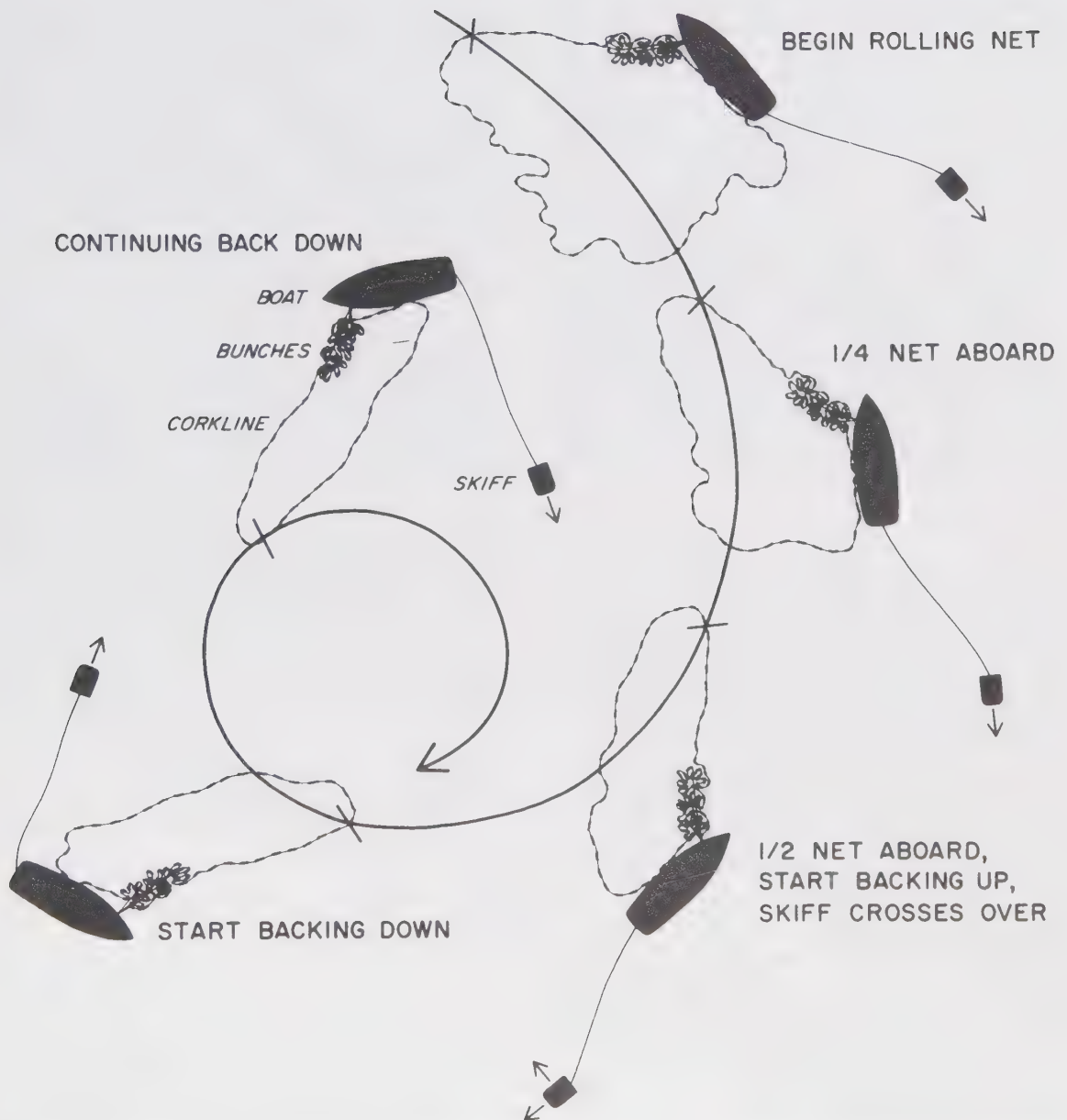


Fig. 2 - The general motion of the vessel and net through the water during the set is a tightening clockwise spiral with backing down taking place in a final tight circle.

fathom "bunches" in the bow corkline. The bunches are pulled in such a way that, as the purse rings rise to the surface, the corkline is fairly straight from the top of the third bunch to the area of corkline that will sink when the porpoise are released. After the centerpiece of the purse cable starts to come aboard, the 60-fathom tow-line from the net skiff is transferred to a padeye on the stern of the boat, and the stern is pulled clear of the stern bag in the net (Figure 1).

By the time the rings are on the ring stripper (see Green, et al., 1971), the stern should be clear of the net. Then net can be "rolled" onto the boat, thus reducing its circumference. The net is rolled as rapidly as possible to reduce the time the porpoise must spend within the net, as well as to pull the stern of the boat into the net. The action of the net skiff pulling as shown (Figure 1) causes the boat to move astern in a large clockwise semicircle, keeping the corkline straight out to the "backing down" area.

'Cork-Tender' Skiff

A man in a "cork-tender" skiff remains at the corkline during the set to retrieve the bow bunch lines and to keep the porpoise away from the corkline or from any pockets that may form. As the net is rolled, the cork-tender circles in the stern bend of the corkline to keep porpoise away from the net as it is pulled out of the water.

The powerblock is adjusted so that it rolls the net evenly. In other words, the chain comes aboard as fast as the corkline, so there is no "balloon" of excess webbing below the corkline in the area where the corks will sink. When such a balloon develops, the porpoise may become trapped outside the corkline and unable to surface.

Twenty to 30 fathoms before the "half-net" marker comes aboard, the captain goes to the port-side throttle and steering controls. The net skiff now comes to the port side and begins towing at an angle of approximately 80° to the main axis of the boat. The captain starts the boat astern slowly, giving it left full rudder and, as the half-net marker comes aboard, the net begins to stretch out evenly. This puts tension on the webbing and closes the meshes as much as possible--before the porpoise start coming in contact with the walls of the net--and prevents a great deal of the entanglement that otherwise might occur.

This marks the beginning of the "backing down" process.

After an additional 10 to 50 fathoms of net have come aboard, the exact amount depending on the number of porpoise, the captain orders the net secured with the choking winch. The cork-tender now moves to the area where the corks will sink during back-down and attaches a line to the corkline so that he may pull it to the surface when the tuna approach that area. The motor of the cork-tender must be shut off to avoid scaring the porpoise away from the opening.

Signal Tuna Clear of Corkline

After the net is choked, the net-tender skiff in position, and the boat headed astern so that the net is stretched out evenly, the man in the cork-tender signals when the tuna are clear of the corkline and headed towards the boat. Upon this signal, the captain opens the throttle approximately 1/ to 1/3 and begins to back the boat around in a tight clockwise circle (Figure 2), always watching to see that the corkline does not sink more than 2 to 3 feet. If the fish turn and head back toward the far end of the net, the man in the cork-tender pulls the corkline to the surface, and the captain closes the throttle. When the fish start back towards the boat again, the signal is given and the process is repeated until as many porpoise as possible are out of the net. Throughout this operation, the net skiff is pulling the seiner at full power at a sharp angle on the port side. Patience in this operation is rewarded by time and labor saved in brailing and in sorting out the porpoise from the tuna by hand.

Noise Diverts Reluctant Porpoise

At times, at the start of backing down, noise is generated near the third corkline bunch to divert reluctant porpoise away from the vessel into the backing-down area of the net. If a pocket of porpoise develops under the corkline, they can sometimes be disentangled by releasing 5 to 10 fathoms of corkline from the third bunch and continuing to back down. The boat (and net) are never allowed to come to a complete stop while backing down because stopping would take the tension off the webbing and allow the meshes to open up. If the meshes open, the porpoise may get their snouts or flippers into the opening, where they are held securely when the boat backs up again and the webbing tightens.

When all but the last few entangled porpoise have been released, the third bunch line is let go. This causes slack across the webbing and corkline so that the sunken corkline rises immediately. The cork-tender is now free to work his way down the corkline and pull the remaining live porpoise out of the net.

When the last half of the net has been rolled aboard, and while the bunt end is being "sacked up," if any porpoise remain in the net, one of the net skiff crew hangs a small aluminum platform over the side of the skiff next to the sack and removes them. In a substantial proportion of sets, all the porpoise are successfully removed by the combination of the backing down process and the cork tender.

In general, during bad weather or when a gear malfunction or "roll-up" (webbing wrapped around the purse rings slowing purring procedure) occurs, every effort is made to roll enough net aboard to permit backing

down as soon as possible. If adjustments to the net or gear must be made, the net skiff driver tows the boat in such a way as to keep the corkline stretched out evenly from the bow of the boat to the back-down area.

Efficiency and Speed Important

Efficiency and speed are very important to the entire operation. Average time spent by the vessel discussed here during three recent cruises was calculated for the "critical" time periods. It was found that 53 minutes, on the average, were required from the time the net was let go to the beginning of the backing down process. An average of 37 minutes elapsed from beginning of the set until the purse rings were on the ring stripper. Another 16 minutes were required for rolling net to the back-down position. These averages include sets made in adverse conditions of weather and sets on a wide range of porpoise school sizes.

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303 RANGE OF THE SKIPJACK TUNA SUBPOPULATION IN THE WESTERN PACIFIC OCEAN

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RÉSUMÉ: Some 6,600 blood specimens were collected from skipjack tuna, Katsuwonus pelamis, from areas off the northeastern and southern coasts of Japan, Okinawa, Bonin-Marianas, Caroline Islands, Solomon Islands, and the areas between the Bonin-Mariana-Caroline archipelagoes and the date line from September 1966 through June 1969. Genetic analyses of these specimen, especially of the serum esterase system, permit a detailed description of range of the subpopulation of the species in the western Pacific in different seasons. Evidence that fish of the western Pacific subpopulation in the waters off the northeastern coast of Japan were replaced within a few weeks in early fall by fish of the central and eastern Pacific subpopulation(s) is presented.

Genetic data, published and unpublished results on movements of tagged fish, spatiotemporal distribution of larvae, and size composition of fish commercially caught, are considered in a discussion of the population structure and migratory route of the subpopulation in the western Pacific Ocean.

INTRODUCTION

On the basis of a series of genetic studies as well as data on larval distribution and the commercial catch, Fujino (1970 and in press a) has drawn a rough sketch of the population structure of the skipjack tuna, Katsuwonus pelamis, subpopulation in the northwestern Pacific Ocean.

More recently, blood specimens were collected from skipjack tuna from the area between Japan-Bonin-Marianas and the date line, waters off the Trust Territory of the Pacific Islands, the Solomon Islands, American Samoa, and waters off the northeast coast of North Island, New Zealand. Biological data which include genetic analyses of these specimens, especially of the serum esterase system, and age composition analysis of the commercial catch permit a detailed description of range, population structure, and migratory routes of the subpopulation of the species in the Northern and Southern Hemispheres of the western Pacific Ocean. Further evidence that fish of one subpopulation in the waters off Japan were replaced within a few weeks by fish of another subpopulation is presented.

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RANGE OF THE WESTERN PACIFIC SUBPOPULATION

A series of extensive genetic studies (Fujino, 1970) has indicated that skipjack tuna of the western Pacific subpopulation are present throughout the year in the waters off the Pacific coast of Japan and the Philippine Sea without being replaced by fish from the central and eastern Pacific subpopulation(s). These studies have also shown that the boundary between migratory ranges of the different subpopulation shifts to the east in summer and to the west in fall and winter in the offshore

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waters of the east coast of Japan and in the waters between the Bonin-Mariana chain and the international date line. On the basis of the above results, Fujino (in press b) stated that skipjack tuna is sympatric in the ecological sense rather than allopatric.

Figure 1 summarizes areas where blood specimens were sampled. Recently some 800 blood specimens (in 18 lots) were collected from skipjack tuna from the area between Japan-Bonin-Marianas and the date line, the Trust Territory, and the Solomon Islands area. Subpopulations of the samples were identified by the application of rejection limits of frequencies of

Table 1. Subpopulation identification of samples of skipjack tuna taken from offshore waters of the east coast of Japan and areas between Bonin-Mariana-Palau-New Guinea archipelagoes and the international date line¹

Lot No.	Number of fish examined	Month sampled	Locality		Fork length in cm.
			Latitude	Longitude	
Central and eastern Pacific subpopulation ($E_{SJ}^1 < 0.566$)					
76	19	Jan. 1969	28°-29° N.	169°-173° E.	64-86
78	19	Jan. 1969	10°-11° N.	174°-175° E.	55-69
86	31	June 1969	33° N.	144° E.	38-45
89	28	June 1969	32° N.	151° E.	39-53
Unidentified ($0.566 < E_{SJ}^1 < 0.590$)					
70	87	Nov. 1968	4° N.	175° E.-178° W.	53-79
71	60	Nov. 1968	3°-5° N.	170°-178° E.	50-71
81	42	Feb. 1969	6°-7° N.	164°-165° E.	60-77
Western Pacific subpopulation ($E_{SJ}^1 > 0.590$)					
68	60	Nov. 1968	0°-1° S.	140°-142° E.	49-58
73	26	Oct.-Nov. 1968	1°-2° S.	143°-150° E.	35-63
74	23	Nov.-Dec. 1968	5° N.-6° S.	143°-152° E.	57-67
75	37	Dec. 1968	5°-6° S.	157°-160° E.	55-66
77	40	Jan.-Feb. 1969	6° N.	149°-153° E.	52-68
79	18	Feb. 1969	10° N.	149° E.	60-69
80	14	Feb. 1969	8° N.	151° E.	45-65
82	100	Mar. 1969	10°-11° N.	156°-157° E.	61-73
83	99	Mar. 1969	9°-12° N.	160°-164° E.	61-72
87	26	May 1969	33° N.	142° E.	37-44
88	20	June 1969	32° N.	146°-147° E.	40-47

¹ Taken after the samples shown in Fujino (1970: table 11). Lots 68, 73, 74, 77, 82, 83, 86, 87, 88, and 89 were taken by pole and line or trolling and all other lots by longline. Lots 70, 71, and 81 were taken over several days of November 10 through 20, November 3 through 26, and late February, respectively.

Table 2. Gene frequencies of serum esterase system of the samples of skipjack tuna from the southwestern Pacific Ocean

Lot No.	Number of fish examined	Month sampled	Frequency ¹ of gene E_{SJ}	Fork length in cm.
American Samoa ²				
1	23	Feb. 1970	0.500	57-68
2	23	Feb. 1970	0.544	46-53
3	20	Mar. 1970	0.500	48-60
4	50	Mar. 1970	0.530	44-53
5	29	Mar. 1970	0.448	40-60
6	60	Mar.-Apr. 1970	0.475	48-65
New Zealand ³				
1	22	Apr. 1970	0.432	47-61
2	20	Apr. 1970	0.500	49-57
3	20	Apr. 1970	0.450	49-57

¹Compared with rejection limits (Fujino, 1970: fig. 1), all samples were indistinguishable from fish of the central and eastern Pacific subpopulation(s) but distinguishable from fish of the western Pacific subpopulation.

²Taken by pole and line during Charles H. Gilbert cruise 117.

³Taken by gill netting in the waters off the northeast coast of North Island, New Zealand.

the determinant gene of the fastest clear band of the serum esterase, E'_{sj} (Fujino, 1970: fig.1). The results are summarized in table 1. Samples taken from American Samoa (205 fish in 6 lots) and from New Zealand (62 fish in 3 lots) were all indistinguishable from fish of the central and eastern Pacific subpopulation(s) but distinguishable from fish of the western Pacific subpopulation (Table 2). For lots 70, 71, and 81, frequencies of E'_{sj} fell where the rejection limits (Fujino, 1970: fig.1) for the different subpopulation overlap and were not identified in this regard. The three lots were taken over a period of several days in November 1968 and February 1969 by longline fishing in locations shown as hatched areas in figure 1; no further information was available. The most likely interpretation of the

above results would be that each lot was sampled from fish from both the western Pacific and the central and eastern Pacific subpopulations. The results together with earlier results permit me to state that the range of the western Pacific subpopulation extends eastward to approximately long. 165°E. without marked seasonal shifts in the equatorial region, placing the boundary in the area between the eastern Caroline Islands and the Marshall-Gilbert Islands. An easterly seasonal shift of the boundary is more pronounced in higher latitudes than in the equatorial region of the northwestern Pacific Ocean.

Fujino (1970) presented evidence which showed that in September off the northeast coast of Japan, fish of the western Pacific subpopulation were replaced within a few days by those of

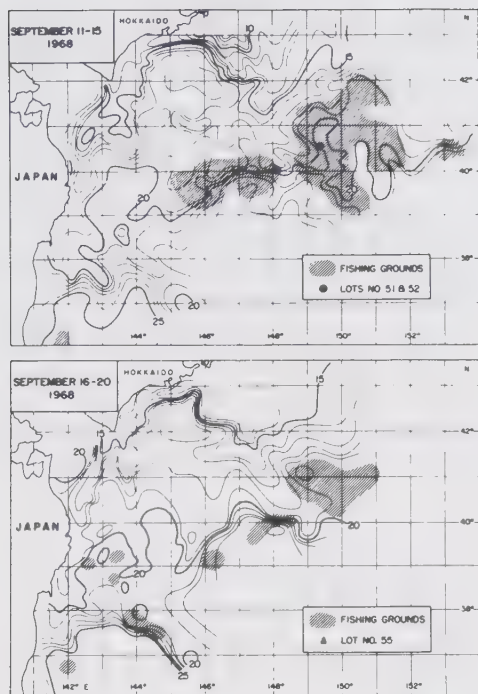


Figure 2. Surface water temperature contours (in °C) in the fishing grounds off the northeast coast of Japan in early and late mid-September 1968, when fish of the western Pacific subpopulation (lots 51 and 52) were replaced by fish of the central and eastern Pacific subpopulation(s) (lot 55). (Source for contours: Japan. Fishing Ground Knowledge Popularizing Association, 1968.)

the central and eastern Pacific subpopulation(s). Data from three lots of samples, numbers 86 (taken June 3), 87 (taken May 28), and 88 (taken June 3) (see table 1), give evidence that a similar replacement, but in reverse, occurred in the waters off the southern coast of Japan (east side of the Izu Islands) between late May and early June 1969.

Skipjack tuna fishing (mostly pole and line with some purse seine) along the Pacific coast of Japan begins in spring in the waters off the south coast of Kyushu, moves northeastwards

along the Kuroshio, reaches the waters off the northeast coast of Japan in summer, and ends there in October or November. In 1968, fish that appeared in the waters off the northeast coast of Japan in summer and the early half of September were identified as those of the western Pacific subpopulation, represented by lots 51 (taken from lat. 40°N, long. 149°E on September 12) and 52 (taken from lat. 40°N, long. 148°E on September 15) and by many other lots taken earlier (Fujino, 1970). Locations of fishing grounds in these waters from September 11 through 15, 1968, are shown with surface temperature contours in figure 2a. Fishing grounds for the following 5 days are indicated in figure 2b, which also shows the locality where fish of the central and eastern Pacific subpopulation(s) first appeared in the latter half of mid-September. They stayed there for several weeks, as evidenced by lots 55 (taken from lat. 37°N, long. 144°-145°E on September 18-20), 58 (taken from lat. 38°-39°N, long. 152°-155°E on October 15-18), 59 (taken from lat. 38°-39°N, long. 153°-154°E on October 17-18), and 64 (taken from lat. 40°-41°N, long. 150°E on November 2-5) (Fujino, 1970: table 11). Despite replacement of fish from different subpopulations in such a short period of time, no distinct change was seen in surface temperature patterns during the period. The southward shift of the Oyashio-Kuroshio front, however, began a few weeks later (see Japan. Fishing Ground Knowledge Popularizing Association, 1968: Rapid reports Nos. 34, 37, and 38). The above evidence together with earlier data suggests that fish of the western Pacific subpopulation moved south of southwestwards from the fishing grounds but not east or southeastwards.

INTERNAL STRUCTURE AND MIGRATION OF THE WESTERN PACIFIC SUBPOPULATION

After summarizing the results of a series of extensive investigations of larval and juvenile tunas conducted since 1960, Ueyanagi (1969: appendix figs. 7a, 7b, and the text) stated that skipjack spawn in the western Pacific between lat. 35°N and 18°S in the northern summer and between lat. 22°N and 24°S in the northern winter.

On the basis of analyses of monthly modal progression in size dis-

tribution of skipjack tuna taken commercially, Kawasaki (1955a, 1955b, and 1964) stated that there were five groups in the adjacent waters of Japan that display life patterns different from each other: Goto group, chain group in the Okinawa-Tokara area, chain group in the Izu-Bonin area, northeastern inshore group, and northeastern offshore group. Fish of "Goto and the northeastern groups" are migratory and their gonads become active in the northern winter, and gonads of the "chain groups" become active in the northern summer, thus indicating existence of two groups, migratory group and chain group, distinguishable from each other by the state of their gonads.

I examined the existence of two such groups by applying the growth curve for fish taken commercially from the entire western Pacific Ocean as follows. Figure 3 shows the growth curve (solid line) for skipjack tuna, obtained from tagging experiments for fish of the central and eastern Pacific subpopulation(s) through the von Bertalanffy growth function (Rothschild, 1967). The curve is shown for the size range of fish taken commercially. It conforms well to the growth rate estimated from monthly modal progression in size distribution for fish from the western Pacific Ocean (Kawasaki, 1963; Rothschild, 1967), although the estimates are based on fish from different subpopulations. Another set of growth curves (dotted line), shown in figure 3, represents a hypothetical group of fish spawned 6 months later. Although sufficient data are not available for the estimate of growth rates in the larval and juvenile stages, size-age relationships for fish that appear in commercial catches from the western Pacific Ocean can be arbitrarily defined from figure 3.

Fork length in cm.	Age in full year
44 and smaller	0
45 to 63	1
64 to 73	2
74 and larger	3

Application of the growth curve of figure 3 to modal size data of the catch from Japanese coastal waters

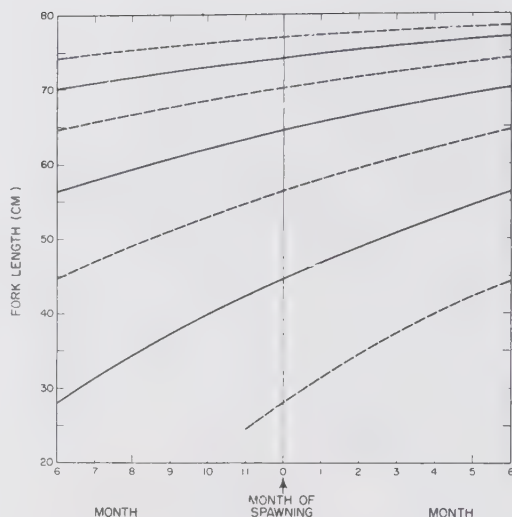


Figure 3. Growth curve (solid line) for skipjack tuna, drawn from tagging experiment data through the von Bertalanffy growth function (Rothschild, 1967) under an assumption that the curve passes the point of 0 cm fork length at 0 months of age (or month of spawning) (Fujino and Kang, 1968). Sizes of fish, represented by the solid curve in the month of spawning, indicate fork lengths at ages in full years. Dotted curve represents growth for fish spawned 6 months later.

(Kawasaki, 1964: figs. 1 through 4) permits me to make the following statement: there are two groups of fish spawned in different seasons; fish from both groups appear in all four areas of Tohoku (northeastern Japan), Izu-Bonin, Okinawa-Tokura, and Goto; and fish from one group (A) are dominant in the first three areas and those from the other group (B) are dominant off Goto. Thus the existence of two groups of fish in the Japanese coastal waters is verified, although there is some difference between my view and Kawasaki's, noted in an earlier paragraph of this article. Kawasaki indicated that his "migratory group" (corresponding to Goto and northeastern groups) and "chain group" appear in different areas separately. My analysis showed that fish of the two groups appear together in all areas

but that the proportions of the two groups are different by area. Similar analyses of size distribution data from the Marianas and Palau (Fujino, in press a: fig. 5) permit me the following statements. In the Marianas, fish from group B predominate in the northern winter but the situation is not clear in other seasons due to insufficient data. In Palau, group B predominates in all seasons appearing almost exclusively in the northern winter. In other areas in the western Pacific Ocean, including the areas of Daito Island (northeast of Taiwan), Luzon Strait (Kawasaki, 1955a), the Caroline Islands (unpublished data), New Zealand (York, 1969), and New Caledonia (Legand, MS.: table 2), fish from the two groups appear in varying proportions, but insufficient data do not permit any precise statements about their relative abundance.

No genetic difference has been found between the two groups (A and B) taken from the western Pacific subpopulation in the Northern Hemisphere. It can be said from the foregoing evidence that (1) within the western Pacific subpopulation there are two groups that spawn in different seasons, one in summer and another in winter, but are not genetically isolated, and that (2) fish from the two groups migrate to various parts of the western Pacific Ocean in varying proportions. Although there is no direct evidence as to which group spawns in which season, Kawasaki's observations on gonads of fish appearing in the Japanese coastal waters (for example the Goto Islands, where one finds inactive gonads in the northern summer) suggest that fish of group B spawn in the northern winter and those of group A in the northern summer. It is unknown yet, however, whether fish in each group spawn in both seasons or whether each group has a single spawning season separately from the other but with some gene exchange.

Recent tagging experiments conducted in the western Pacific indicated that skipjack migrate (1) from the waters off the east coast of Taiwan to the areas of Goto, Okinawa-Tokara, the southern coast

of Kyushu, the Izu Islands, and Tohoku (northeast coast of Japan); (2) from areas off Nojima-saki in two directions: one to the area of the Izu Islands and another to Tohoku; and (3) from Palau to the Marianas (Tohoku Regional Fisheries Research Laboratory, n.d.; Kato, 1969; and Otsu, in press).

DISCUSSION

To formulate a model of population structure and migration for the western Pacific skipjack tuna subpopulation, some discussion of the present studies follows:

- (1) Range of the western Pacific subpopulation in the Southern Hemisphere.

Genetic data, especially on the serum esterase system, on skipjack tuna taken from waters of American Samoa and New Zealand (table 2), as well as earlier results (Fujino, 1970), have indicated that the range of the central and eastern Pacific subpopulation(s) extends westwards near the date line and the waters around New Zealand in the southern summer and early fall.

No such data are available to delineate the range of the western Pacific subpopulation in the Southern Hemisphere. As noted earlier, however, skipjack tuna spawn in the southern summer from lat. 22°N to 24°S without marked geographical discontinuity between the Northern and Southern Hemispheres in the western Pacific (Ueyanagi, 1969: appendix fig. 7b). Although the mechanism of gene exchange between the two groups (A and B) within the western Pacific subpopulation in the Northern Hemisphere is as yet unknown, their simultaneous occurrence throughout the areas where data are available plus the continuity of spawning grounds suggest that skipjack tuna in the southwestern Pacific are not genetically isolated from the subpopulation in the northwestern Pacific Ocean. From the above statement it can be said that the range of the western Pacific subpopulation extends across the Equator far into the Southern Hemisphere. The boundary between the western Pacific subpopulation and the central and eastern Pacific subpopulation(s) may be found between New Guinea-Australia and the date line, somewhere near the New Hebrides, the

1/ Legand, M. Manuscript. Indications sur la bonite a ventre rayé dans le sud Ouest Pacifique. Institut Français d'Océanie, Office de la Recherche Scientifique et Technique Outre-Mer, Nouméa, New Caledonia.

Loyalty Islands, and the west coast of New Zealand. It is likely that seasonal boundary shifts analogous to those in the Northern Hemisphere take place, although no data are available yet.

- (2) Some factors limiting the range of a subpopulation.

Insufficient data do not permit any comprehensive discussion of isolating mechanisms between subpopulations, or factors which limit the range of each. Evidence of replacement of fish of one subpopulation by fish of another, however, provides some fragmentary information indicating that at least two factors play a role.

As described already, in 1969, during the wintering of fish of the western Pacific subpopulation in the Philippine Sea, fish of the central and eastern Pacific subpopulation(s) appeared in the waters just to the east of the Izu Islands. They did not migrate further westwards beyond the islands, and between late May and early June were replaced by fish of the western Pacific subpopulation. The observation strongly suggests that the Izu-Bonin-Mariana archipelagoes act as a barrier to the central and eastern Pacific subpopulation(s). Insufficient data do not permit any further discussion on the subject.

As noted, skipjack tuna fishing along the Pacific coast of Japan begins in spring in the waters off the southern coast and the fishing grounds move northeastwards accompanied by a shifting of the Kuroshio front. In 1968, skipjack tuna fishing grounds reached their northeastern extreme (approximately lat. 42° - 43° N, long. 156° - 157° E) in August. Up to then, the major fishing grounds moved approximately 11 km on an average daily (measured in a straight line). A southwestward movement of the fishing grounds from the extreme location began in early September that year and the daily movement then averaged about 34 km (three times the earlier daily movement--a probable sign of a distinct response to some stimuli) for the early half of September. Then fish of the central and eastern Pacific subpopulation(s) appeared there. The southwestward shift of the skipjack fishing grounds took place a few weeks before an apparent south-

westward movement of the Kuroshio-Oyashio front from its northern extreme, and fish of the western Pacific subpopulation disappeared from the waters.

The above observations suggest that skipjack tuna recognize changes in the water through sensory channels (properties such as temperature gradients, a difference in chemical constituents, etc., Harden Jones, 1968), react to the stimuli, and begin a south or southwestward migration. Thus water-mass difference is another possible factor in limiting the range of fish of certain subpopulations.

- (3) Significance of the existence of two groups within a subpopulation.

Growth curves for skipjack tuna from tagging experiments were discussed by two independent studies. Rothschild (1967) used data obtained from the experiments conducted in Hawaiian waters. Joseph and Calkins (1969) based their analyses on the results of experiments conducted in the eastern Pacific and stated that parameters of the Rothschild's curve fell within the confidence regions of their estimates. Thus Rothschild's (1967) curve was used for the present analyses of size distribution data.

Despite some possible deviation in the estimate of the growth curve applied, the existence of two groups of skipjack within a single subpopulation is obvious. Lack of difference in genetic composition between the two groups suggests at least one of two possible mechanisms of gene flow between them. (1) Fish of each group spawn in both seasons, summer and winter, thus providing unlimited opportunities for gene exchange. (2) Each group has a single spawning season separate from the other (summer or winter) with a low frequency gene exchange. (A low-frequency continuous or intermittent gene exchange is sufficient for the attainment of genetic homogeneity.) Occasional overlapping of the spawning seasons of the two groups, for example, beginning of spawning of one group before ending of spawning of another, could be the mechanism.

Such a mechanism could also play a part in exchanging genes between skipjack tuna in the Northern and

Southern Hemispheres within the western Pacific Ocean, resulting in homogeneous genetic compositions. Recognition of two groups A and B provides a potential tool for improving our understanding of their ecology and for estimating parameters in stock assessment through analyses of dynamic features of the two groups.

The foregoing discussions strongly suggest the existence of an intermediate state of diversifying into subpopulations from a homogeneous population in skipjack tuna: the existence of two groups that behave differently in the ecological sense without genetic diversity (Mettler and Gregg, 1969: fig. 8.3 and the text, pp. 183-185).

A MODEL OF POPULATION STRUCTURE AND MIGRATION OF SKIPJACK TUNA IN THE WESTERN PACIFIC OCEAN

On the basis of the foregoing analyses, discussions, and other available data, the following model of population structure and migration is proposed.

(1) In the northern winter, fish of the western Pacific subpopulation stay within the Philippine Sea, areas of the Caroline Islands, the Coral Sea, and the Tasman Sea (the eastern limit of the range being near the New Hebrides and off the west coast of New Zealand, with some year-to-year difference). In the northern summer, the range in the Northern Hemisphere extends eastward to about 165°E ; east westerly seasonal shifts of the eastern limit of the range are more marked in higher latitudes than in the equatorial region in the Northern Hemisphere. Similar seasonal shifts must take place in the Southern Hemisphere, although no data are available (see fig. 4). The western limit of the range of the western Pacific subpopulation could reach to the Greater and Lesser Sunda Islands, the east coast of Australia, and the eastern half of the south coast of Australia at least.

(2) There are two spawning seasons, one in northern summer and another in northern winter. Intensive spawning takes place in the areas approximately between $\text{lat. } 30^{\circ}\text{N}$ and 10°S in the northern summer and between $\text{lat. } 20^{\circ}\text{N}$ and 22°S in the northern winter within the range of the western Pacific subpopulation noted above (extending west-

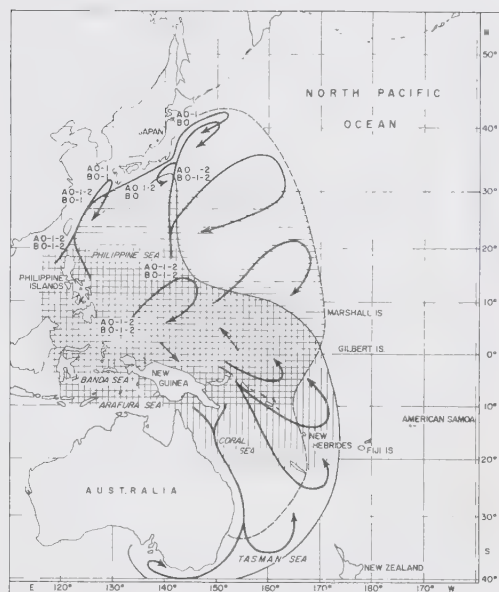


Figure 4. Proposed range and migration routes of skipjack tuna subpopulation in the western Pacific Ocean. Eastern limit of range in the northern winter (southern summer) and northern summer (southern winter) are indicated by a thin solid line and a broken line, respectively. These two lines also represent approximate western limits of ranges of the central and eastern Pacific skipjack tuna subpopulation(s) in the two seasons. Intensive spawning grounds in the northern summer and winter are shown as the areas hatched horizontally and vertically, respectively. Thick solid lines with arrows represent proposed major routes of migration of both group A and B as described in the text. Thick broken lines with arrows show possible infrequent intermingling across the Equator between northern and southern fish. Numerals with a letter A or B mean age classes of fish by group (A or B) in each location, as described in the text. (Sources: Japan. Fishing Ground Knowledge Popularizing Association, 1968; Kawasaki, 1955a, 1955b, 1964; Fujino, in press a.) Such numerals are not shown for the Southern Hemisphere for lack of data.

ward to the areas around the Philippine Islands). As a result, in both the Northern and Southern Hemispheres there are two groups of fish spawned in different seasons and behaving differently from each other in an ecological sense without diversification in genetic composition.

(3) The two groups (A and B) spend their larval and juvenile stages separately from each other in the tropical and subtropical waters. After the juvenile stage, the majority of fish spawned in the northern summer in the Northern Hemisphere (group A) migrates to temperate waters by two major routes: one along the Luzon Strait, the east coast of Taiwan, the Ryukyu Islands, and the south and east coasts of Japan or the Goto Islands in the East China Sea; and the other along the Mariana-Bonin-Izu Islands and the southeast and east coasts of Japan. They migrate in different proportions, by age and by area, beginning in the northern spring and continuing through the fall. These fish winter in the tropical and subtropical waters, in fact, some parts of group A stay the year around in the archipelago areas of the Northern Hemisphere. They spawn in the areas noted in item (2) from May through August, with a peak in June or July.

Some parts of group B, spawned between November and February in the Northern Hemisphere, migrate to almost all areas where group A fish appear. They move into the temperate waters about 1 month later than group A fish in the northern summer and fall in varying proportions by age and by area. They spend the northern winter and spring in tropical and subtropical waters; on the whole, greater parts of group B stay in the tropical and subtropical areas. As a result, fish of group A dominate fish of group B from spring through fall in the temperate waters of the Northern Hemisphere, except in the area of the Goto Islands.

(4) Groups A and B, products of southern winter and summer spawning in the Southern Hemisphere, also spend their larval and juvenile stages separately from each other in the subtropical and tropical waters. After that, some parts of the two groups migrate to temperate waters of the Tasman Sea and adjacent regions in varying proportions by age and by area, while the rest remain behind. As a whole, fish of group B predominate

from southern spring through fall in the temperate zones of the Southern Hemisphere.

Two major routes are postulated for the migration: one along the Solomon Islands-New Hebrides archipelagoes and another along the coast of New Guinea and the east and south-east coasts of Australia.

Intermingling (with gene exchange) takes place between northern group A and southern group A and between northern group B and southern group B at the time of spawning and during the larval stage. After the larval stage, intermingling of fish from the northern and southern groups probably continues but less frequently. Figure 4 summarizes proposed migration patterns of the skipjack subpopulation in the western Pacific Ocean.

TESTING OF THE HYPOTHESES

A variety of studies must be conducted to test the hypotheses proposed in the present model. Some aids for planning the work are listed below.

(1) To test the relationship between fish from the Northern and Southern Hemispheres in the western Pacific, genetic data should be collected from various parts of the Tasman Sea and adjacent regions, that is, the east coast of Australia, New Caledonia, the New Hebrides, and the Fiji Islands.

(2) To delineate the western limit of the range of the western Pacific subpopulation, genetic data should be collected from the South China Sea, Java Sea, Banda Sea, Arafura Sea, and the Indian Ocean.

(3) A series of observations of gonads from both groups in different seasons must be conducted to examine the relationship between the groups, first recognized by size composition

(4) The extent of intermingling between northern group A (or B) and southern group A (or B) can be studied by tagging experiments only.

(5) To test the migratory route along the Mariana-Bonin-Izu chain up to Japanese coastal waters, extensive tagging should be conducted in the archipelago areas.

(6) Finally, for studying isolating mechanisms between the western Pacific and the central and eastern Pacific subpopulation, a series of extensive subpopulation studies of larval and juvenile skipjack tuna must be conducted. This study should be made in the areas where the boundary between the two subpopulations exists and should include simultaneous oceanographic observations.

ACKNOWLEDGMENTS

Dr. S. Ueyanagi gave me many useful suggestions to formulate this model of population structure, Mr. T. Otsu, Dr. R.A. Skillman, Dr. S. Ueyanagi, Dr. F. Williams, and Dr. J.P. Wise read the manuscript and gave useful comments. The cooperation of Dr. Ueyanagi and Mr. Y. Warashina, Far Seas Fisheries Research Laboratory, Japan, Dr. D. Eggleston and Mr. A.G. York, Marine Department, New Zealand, and Dr. S. Swerdloff, Government of American Samoa, in collecting research materials, and the careful technical assistance of Miss Ruth A. Noble and Mr. Peter C. Galloway are greatly appreciated.

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EXPERIMENTAL DRUM SEINING FOR WETFISH IN CALIFORNIA

F. J. Hester, D. A. Aasted, and R. E. Green

The authors consider the problem of operating a vessel profitably in a fishery for a fixed-price resource. They believe that more profit can be made by increasing the efficiency of vessel operation, thereby increasing landings, and by decreasing manpower through mechanization. In this study, purse-seining operations were mechanized by using a hydraulically powered drum to handle the net and a fish pump to load the fish. This increased operating efficiency by lessening time required to catch the fish--and by decreasing manpower required for the vessel operation. The experiments showed that the cost of mechanizing could be offset by recovery from the crew's share of the catch while increasing wages for the remaining crewmen.

THE PROBLEM

The San Pedro wetfish purse-seine fishery is the last major stronghold of the former California sardine fleet. Wetfish is a collective term for those species--anchovy, sardine, mackerel, and squid--used for canning and reduction that are bulk-loaded in the round, usually not refrigerated, and generally off-loaded with a suction pump. The vessels in this fishery are mainly ex-sardine seiners 45 to 90 feet long with carrying capacities of 25 to 150 short tons. About 24 of these vessels operate within a 100-mile radius from San Pedro, California. Perrin and Noetzel (1970) showed that this fishery was becoming increasingly unprofitable primarily because of rising costs of operations and demands for higher wages--while prices for the raw materials remained nearly constant. This situation is fairly common in countries where the standard of living is rising at a rapid rate and raw products prices, controlled by world markets, tend to rise at a lesser rate. The solution is to increase the productive efficiency of the operating units by increasing the production per unit of operating time and by decreasing the cost of operation.

Such changes in efficiency can be realized in a number of ways, including increasing the size and speed of the vessels, changing fishing strategy, and mechanizing the operation to use manpower more efficiently. In the case of the San Pedro wetfish fleet, each of these approaches was considered.

The first was rejected for the time being because it was felt that the necessary capital for improved vessel design would not be forthcoming until the fishery's profitability was more apparent. The second could be a lengthy project, using operations research methods, and would require many logbook-type operating data over a long period. Such data are not now readily available (Petrich, 1965). It is the last of these three--mechanization--which will be reported here.

Cooperative Group Formed

In September 1969, a cooperative group known as the Wetfish Operation Pool was formed within the California Marine Research Committee. It comprises California's Department of Fish and Game, the Fishermen's Cooperative Association of San Pedro, the Fishermen's Unions, and the Operations

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Research Group of the National Marine Fisheries Service, La Jolla, California. This pool, under a joint funding arrangement, chartered a San Pedro wetfish boat, 'Sunset', to experiment with mechanizing the fishing operation. The objective was to reduce by 40 to 50% the number of men required for working the vessel. Additional advantages sought were to decrease the time of the fishing operation, especially desirable for species available to the gear for only limited times during the day, and to develop a safer and less backbreaking method.

MECHANIZATION OF PURSE-SEINE OPERATIONS

A review of world purse-seining methods shows methods for handling the different phases of this fishing which, if combined, probably could achieve the desired results. These include a seine drum for reducing labor in handling the net, net modifications to permit easier handling of the catch, and pumping devices to load fish from net to vessel. It is hard to say what innovation has had the greatest effect upon purse seining but, quite likely, it would be one of the mechanical methods of handling the net.

Purse seining has developed from a completely manual operation through an intermediate phase using powered roller to ease pulling the net--to, more recently, the introduction of side haulers, power blocks, or the net drum. The power block and the net drum originated at about the same time in the Pacific Northwest.

The power block, invented by Mario Puretic of San Pedro, California, revolutionized the handling of purse seines and has achieved worldwide recognition.

The drum seine, an invention of Nick Kelly from British Columbia (Philips, 1971), has not received the same acceptance for several reasons. The drum, because of its extremely rapid net-retrieving capability, was outlawed from the Alaskan salmon fishery as a conservation measure, whereas the Puretic block was legal and gained rapid acceptance. The drum was legal, however, in Canada and

in the Washington salmon fishery, where it was accepted by boats that did not spend part of their time fishing in Alaskan waters. The power block has greater versatility with the type of net it can handle and is less costly to instal. However, vessels that used the drum have been very satisfied with its performance and recommend it over the block.

The drum appeared ideal for our needs with the San Pedro wetfish experiment. This was because the crew requirements were not dictated by the need for sufficient manpower to stand watches and repair gear on extended voyages. These vessels seldom are away from port for more than 24 hours. Second, the drum would reduce considerably the time in the set. It is a very important point because several principal wetfish species show near the surface only for a short time during day or night. The ability to make several sets in rapid succession may mean the difference between a partial or full load for the vessel.

Basically, the drum is a large reel powered either mechanically from the main engine or by a hydraulic motor. A purse seine is wound on the drum with the purse line left threaded through the purse rings. In addition to the drum, a mechanically or hydraulically driven level wind is used consisting of two upright rollers through which the net passes as it is retrieved.

In some vessels, the drum and level wind are installed on a rotating table so the net can be set over the stern and retrieved over the side. There are pros and cons to this innovation. Whether or not the benefits warrant the additional installation cost should be studied. We selected a drum installation consisting of a fixed drum with a level wind across the stern.

Fish Pump

The second major item of equipment gaining wide acceptance in purse seining is the fish pump. Several models are available. We chose for its ready availability the Marco¹ capsule pump. Fish pumps can load fish more rapidly than the conventional brailing net. Also, they require less manpower and eliminate the safety hazards of brailing.

¹ Use of trade names throughout this article does not imply endorsement by the National Marine Fisheries Service.

In addition to drum and pump, we incorporated into our experiment a hydraulically powered, reel-type pursing winch; a boom to handle corklines; and a "ring stripper" that automatically feeds the purse rings on to the drum during retrieval phase of operation.

DESCRIPTION OF SAN PEDRO INSTALLATION

The vessel made available to the Wetfish Operation Pool under a charter arrangement was M/V Sunset, a former California sardine seiner. It is of wooden construction with overall length of 90 feet, beam of 21 feet, and carrying capacity of approximately 150 tons. Sunset is powered by a 250-hp diesel producing a cruising speed of about 9 knots.

When delivered to us, she was rigged for wetfish seining with a power block driven by

a small hydraulic pump running off the main engine. Other deck machinery included a mechanically driven double capstan winch for pursing and brailing. Because the existing hydraulic system was too small to handle the proposed additions to the machinery, the first modification was installation of an auxiliary engine and a 100-gallon per minute (gpm), 1800 psi hydraulic system. The auxiliary was a General Motors 160 hp. 6-71 diesel engine driving stacked 60- and 40-gpm hydraulic pumps off the power takeoff. In addition, a separate 30-gpm pump was mounted off the shaft. The 60-gpm pump was to drive the drum and fish pump; the 40-gpm pump was used for the winch, and the 30-gpm pump was used to operate the level wind.

The next modification was to attach a "beaver tail" (Fig. 1) to the shoe to protect rudder and propeller from the net. Beaver tails are commonly used in the Northwest



Fig. 1 - "Beaver tail" shown installed to bottom of shoe. Stern idling roller is also shown installed. (D. Aasted)

but have not found their way into our wetfish fleet. Because of the drum, the net passes over the counter and down the side of the vessel, and some protection is needed to keep the webbing from becoming tangled up in the propeller.

The third modification was to remove the turntable from the stern and to fabricate and instal in its stead the drum and level wind (Fig. 2). This unit was designed and built by Post Point Marine of Bellingham, Washington. The drum is aluminum with 8-foot diameter flanges and an 11-foot length core, 22 inches in diameter. The drum is driven by two Hydrostar hydraulic motors. The level wind

The existing double capstan winch formerly used for pursing was removed and replaced by a hydraulically powered double drum dragging-seine winch. Because the tow line for the net is wrapped on the core of the drum, only two drums are needed for the pursing winch if the net is to be operated full-pursed; in practice, we operate the net half-pursed so that only one drum is used.

Fish Pump & Separator

The fish pump selected was a Marco U-235, 10-inch capsule pump. To handle it, we installed a 24-foot boom from which we also handled the corks of the fish bag. The wire



Fig. 2 - Drum and level wind on M/V Sunset. (R. Green)

consisted of two upright rollers mounted in a track across the stern. The level wind is driven by a chain and cable arrangement from a hydraulically powered sprocket. The controls for the drum and level line are mounted on the portside of the drum to allow operator a good view of the net. A complete hydraulic system diagram for Sunset is given in Figure 3.

basket-type fish-water separator was mounted on the starboard side adjacent to the opening to the fish hatch. This pump and separator had previously been tested aboard the vessels NEW ROMA, Monterey, California, and S. T. GUISEPPI, San Pedro; it was satisfactory provided sufficient hydraulic capacity from the vessel was available.

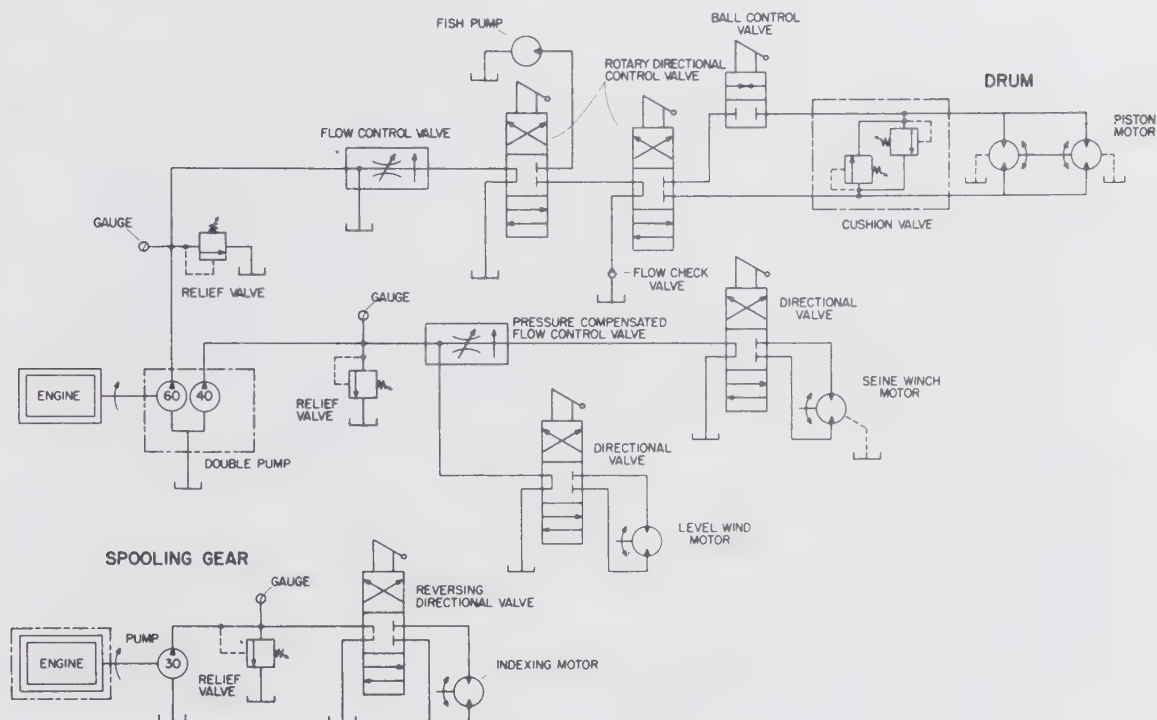


Fig. 3 - Diagram of hydraulics system installed on M/V Sunset.

A Whaley Engineering ring stripper was installed on the portside just aft of the pursing davit (Fig. 4). This ring stripper is described by Green, Perrin and Petrich (in press); it has replaced similar devices throughout the Northwest, including the "hairpin" in which the rings are suspended from the mast. When properly positioned, the ring stripper holds all purse rings during retrieval. It allows purse line to run freely through them while feeding off one ring at a time as net is retrieved.

The Net

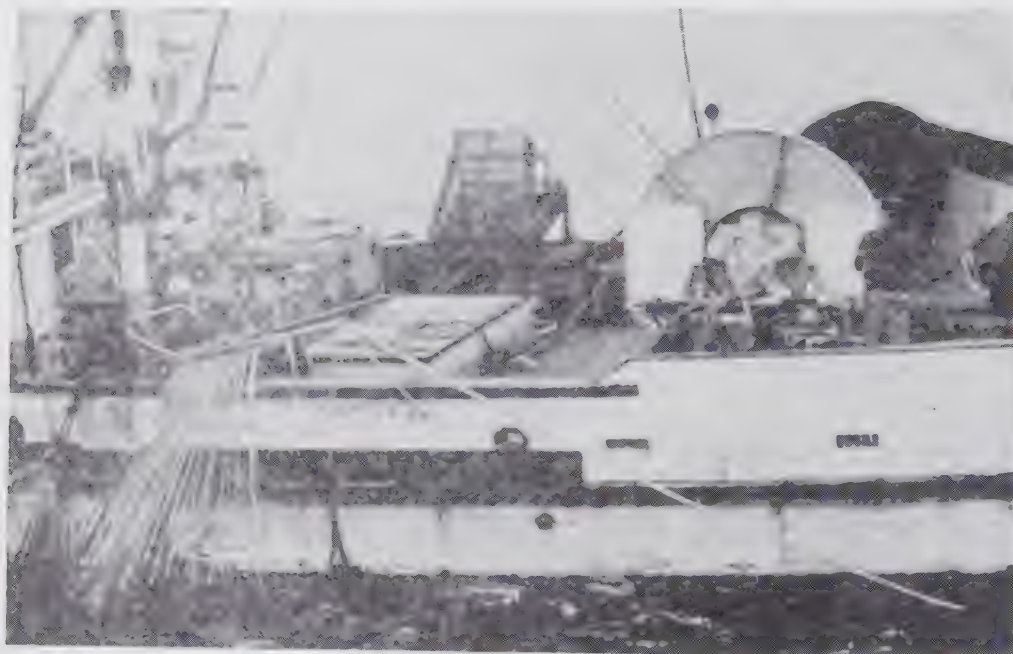
The net used by Sunset was designed for anchovy. Modifications to adapt it for drum seining involved replacing bridles with $\frac{1}{2}$ -inch-diameter polydac rope, smaller diameter brass or stainless steel rings, and a synthetic rope purse line. The purse line consists of 50 fathoms of $1\frac{1}{4}$ -inch-diameter braided nylon in area of main wear, followed by 150 fathoms of 1-inch diameter. The smaller brass or stainless steel rings are preferred because they are less abrasive to the synthetic

rope than are iron purse rings. Rope bridles are preferred to chain because they reduce possibility of bridles becoming tangled in net as it is wrapped on the drum, and they do not rust. The chain leadline was left unchanged.

Because of the large compressive force on the part of the net near the core of the drum, it was necessary to remove the corks from that half of corkline and to mount them on a separate corkline to reduce breakage. We replaced the sponges corks with Sanyo, and later with Swedish floats, model 6215, which proved more resistant to the crushing forces. Finally, pucker rings were added to top of fish bag so floatline above bag could be gathered together and suspended from the boom; this obviated need for skiff to come alongside to support corks.

OPERATION

The initial problem of loading net on drum was attacked by stacking net on stern in usual fashion, setting it in a straight line, and reeling it onto the drum. The net, when stacked, presents an awesome pile which does not look



Figs. 4A & B - Ring stripper in operation. Ring on stripper in top photo (4A) has slipped in 4B. Purse line is feeding through rings. (R. Green)

as though it would fit on the drum. However, as the net winds on under tension, the volume is reduced by at least a third. When the net is set from the pile in a straight line, the purse line is allowed to run out, threaded through the rings so that both net and purse line can then be wound on drum. When setting from the drum (Fig. 5), a few fathoms of the bag are left free on deck and attached to seine skiff in usual fashion. Several seconds pass before inertia of the drum can be overcome and the net begins to pay out. The few fathoms of webbing in the water provides additional resistance that would not be available from skiff alone.



Fig. 5 - The start of a set. Skiff has been dropped and net drum is free wheeling. (R. Green)

When setting from the drum, the greatest hazard is the possibility of a backlash. It requires an alert operator to keep a slight tension on the drum at all times. Make sure that sticks and other stiff objects are not caught in the webbing where they could hold two layers of the net together on the drum. If these precautions are rigorously observed, chances of backlash are very slight. However, because of this possibility, it is advisable to leave power skiff attached by its bow to the net until about a quarter of net is off the drum. Otherwise, if a backlash should occur while the skiff is turning and is broadside to the net, the skiff may be swamped. A tow line is wrapped on the core of the drum to allow setting in a larger circle than net will encompass.

Once tow line has been retrieved, the other end of purse line can be brought forward to the winch; or, if the net is partially pursed, as we have been doing, only one end of purse line is used for pursing, and the other end of net is wrapped on drum while pursing proceeds. With practice, the forward part of net will be pursed at same time that after part of net has been retrieved on drum. Then the rings are brought up and transferred to ring stripper. The balance of the net to the bag then is retrieved with the drum; the purse line is allowed to feed out from winch through rings on the ring stripper. The rings themselves pay out one at a time automatically as the webbing is retrieved (Fig. 4).

During pursing, the corks in bag are bunched and suspended from boom so that as bag is reached, the net is suspended by the last few rings on ring stripper with the corks hanging from boom. At this point, in the conventional manner, the net is passed forward of the drum and strapped in. When the fish are dried up, the pump is lowered into bag and the fish are pumped aboard. Once the bag is empty, the skiff comes alongside, takes the bag end and stretches it out in the water. The last few wraps of the drum are released to allow net to straighten out, and the bag is brought aboard on the drum.

The drum has other advantages: First, the set can be stopped at any point and retrieval begun. Second, because net is easy to handle, it can be let go in a straight line and retrieved to wash it; or, if repairs to the net are necessary, the vessel can hang from the net as on a sea anchor and repairs be effected.

FISHING TRIALS

Vessel modifications and equipment installation, with exception of new winch, were completed in May 1970. The first phase of field trials was a series of water hauls to uncover any unanticipated problems in performance and handling of gear. These trials were held near Los Angeles Harbor in calm water and were completed within a week. Then we proceeded with fish trials to evaluate further the effectiveness of equipment and to see if more improvements were possible.

At the outset, several minor problems were encountered, including difficulty in handling the rings when pursing from one

end of the net only. These problems were solved. At first, the existing double capstan pursing arrangement was not satisfactory. When it was necessary to "hold" the purse line on the capstan, the friction on the synthetic rope was sufficiently great to damage the purse rope. Also, it was inconvenient to tie off the purse rope during these momentary "holds". The best solution was to replace the capstan winch with a modified drum-type pursing winch. A hydraulic powered winch was installed, and the difficulties with purse line were resolved.

During the 1970-71 anchovy fishery, we obtained comparative time-in-set and manpower requirement data from other vessels in the San Pedro wetfish fleet. The combination of drum and fish pump resulted in significant decreases in time required to complete sets in nearly all catch-size categories (Table 1); often, it was possible to get an additional set in the brief time that fish were available just before dawn. We found one problem that did not occur on conventionally rigged boats. During retrieval, the net rubbed continuously against the vessel's counter and the chain leadline caused some scoring of vessel's hull. This was solved during next haul-out by installation of suitable rubbing strips on bottom and portside. Another possible solution would be to mount the drum on a rotating platform and to change

location of level wind so net is retrieved off portside. This also would permit drum to be used to dry up fish completely. The modification should be studied.

ECONOMICS

The purpose of the experiment was to evaluate the profitability of mechanizing small to medium purse seiners. The cost of the essential modifications to Sunset is given in Table 2. Labor performed by the vessel, crew, or National Marine Fisheries Service personnel during the installation is not included. Shipyard labor cost and contract labor costs are included since the costs cover specialized skills not readily available

Table 2 - Cost of essential modifications
for mechanizing M/V SUNSET

Drum, complete with level wind and stern roller	\$17,000
Capsule fish pump and separator	3,500
Beaver tail	836
Modifications to net	680
Ring stripper	1,375
Dragger winch	6,039
Diesel auxiliary	2,500
Hydraulic system	4,571
Miscellaneous	1,759
Total	\$38,260
Yearly cost \$7,652 + (15% interest) 1,148 =	\$ 8,800

among average fishing crew. Table 3 illustrates possible recovery on this investment assuming investment is amortized over 5 years and financing costs run 15%. It is obvious that unless a larger share of catch is allocated to vessel, it is not profitable for owner to make this investment. However, with the illustrative distribution of vessel earnings given in the table, it can be seen that the investment can be recovered and

Table 1 - Tons loaded per minute in set
by size of catch

Size of catch (tons)	Tons/minute in set	
	SUNSET	Others in fleet
0-19	0.12	0.16
20-39	0.37	0.32
40-59	0.76	0.51
60-79	1.07	0.61
80-99	1.13	0.76
100 and over	1.18	0.98

Source: Unpublished logbook data furnished by the California Department of Fish and Game.

Table 3. Economics of drum seining for anchovy (X1000). Annual vessel gross

\$138,000. Trip expenses \$14,000¹. Net proceeds \$124,000

Share arrangement	Conventional seining with 10-man crew		Drum seining with 5-man crew					
	Boat 40%	Crew 60%	Boat 40%	Crew 60%	Boat 45%	Crew 55%	Boat 50%	Crew 50%
Share	49.6	74.4	49.6	74.4	55.8	68.2	62.0	62.0
Owner's costs ²	32.2		32.2		32.2		32.2	
Drum and related costs			8.8		8.8		8.8	
Profit before taxes	17.4		8.6		14.8		21.0	
Crew share 1 man		7.4		14.9		13.6		12.4

¹ Means of 14 vessels, 1971 anchovy season.² From Perrin and Noetzel (1970) increased by 40% coinciding with similar increases in annual vessel gross and trip expenses.

profitability of vessel increased. At same time, the average crewman share will increase greatly compared with his expected earnings on a conventional vessel.

During her first year of operation (1970-71) under this experiment, Sunset's earnings were compared with other boats of the fleet. Of 14 vessels that made bookkeeping records accessible, Sunset ranked seventh in gross income, fifth in boat share, and fourth in crew share. The average number of crewmen during this period was 5.4 on Sunset, and 9.9 on the other vessels. The share arrangement on Sunset was boat 50% and crew 50%. The mean share arrangement for the others was boat 40%, crew 60%.

Additional benefits that do not show in the fiscal data are the increased comfort and safety of crewmen with drum seining operation. It is no longer necessary for crew to

stand in net pile with water dripping on them from above, nor to submit to the arduous and hazardous conditions of brailing. The use of ring stripper and dragger winch obviate most dangers associated with handling the rings. Since the rings never come aboard, but remain on side, the peril of working under the rings is removed. Further, the hydraulic dragger winch installation permits purse line to be handled without having loose coils of line on deck. The line can be stopped at any point during the operation. It is relieved automatically by hydraulic system if tension becomes too great.

CONCLUSIONS

1. The drum seining method of mechanizing purse seining operations is readily adaptable to the California wetfishery. The use of the drum speeds up the actual fishing time and decreases the number of men required to handle the gear.

2. Additional improvements that were tested and found to be of benefit are:

(a) The fish pump for brailing the fish into the vessel, which reduces the time and the manpower needed;

(b) the ring stripper, which simplifies handling the purse rings; and

(c) a hydraulic dragger type winch, which results in savings in manpower and a safer operation.

3. A vessel equipped with this equipment and operating with a reduced number of crewmen is capable of equalling or exceeding the performance of a power-block-equipped vessel.

4. The capital outlay for the drum seining modifications can be recovered by changing the vessel crew share arrangement of the vessel income.

5. The vessel crew earnings can be expected to increase with reduction in crew size. At the same time, they benefit from a reduction in the labor required during fishing and an improvement in safety.

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SWIMMING AND FEEDING BEHAVIOR OF LARVAL ANCHOVY *ENGRAULIS MORDAX*

JOHN R. HUNTER¹

ABSTRACT

The swimming and feeding behavior of laboratory-reared larval anchovy, *Engraulis mordax*, was described over the first 30 days of larval life. Estimates were made of cruising speed, proportion of time spent in rest, and burst speeds. Tail beat frequency, tail beat amplitude, and speed of swimming larvae were measured from cine photographs and the relationship between these variables determined. Complete and incomplete feeding sequences were described in detail from cine photographs and the frequency of feeding acts determined from visual observation. The extent of the reactive perceptive field for prey was measured from cine photographs and expressed as a function of larval length. Feeding success of larvae fed rotifers was determined for the first 21 days of larval life. These estimates were combined to estimate the volume of water searched by larvae per hour, and this estimate and others were used to calculate the density of food required by larvae to meet metabolic requirements. These calculations indicated that the density of food required by larvae just after yolk absorption was up to 37 times that required by older larvae.

In this report I describe the feeding and swimming behavior of the larval anchovy, *Engraulis mordax*, during the first 30 days of larval life. These observations will be combined with results of other studies in a model for estimation of the survival of larval anchovy in the sea. Similar studies of feeding and locomotor behavior have been made on other larval fishes (Blaxter, 1966; Braum, 1967; Rosenthal and Hempel, 1970), and the biology of larval fishes in general has been reviewed by Blaxter (1969).

APPARATUS AND METHODS

Anchovy larvae were reared from the egg using techniques described by Lasker, Feder, Theilacker, and May (1970). The larvae were kept in 500-liter black, fiber glass tanks in non-circulated sea water at 17° to 18°C. They were illuminated by fluorescent lamps and were given a daily dark period of 10 hr with a half hour of dim light preceding and following the dark period. Larvae were fed a variety of organisms ranging from wild plankton to laboratory-cultured brine shrimp, *Artemia salina*, the dinoflag-

ellate, *Gymnodinium splendens*, the rotifer *Brachionus plicatilis*, and the veligers of various species of mollusks (Lasker et al., 1970; Theilacker and McMaster, 1971).

Most of the data in this report will be concerned with larvae younger than 30 days and 15 mm or less in length because larvae in this size range are more easily cultured than older ones. Metamorphosis of *Engraulis* occurs after about 50 to 60 days at 17° to 18°C when the larva is about 40 mm total length.

Visual observations of the feeding and swimming behavior of larvae were made in the 500-liter rearing tanks throughout the 13-hr day. A larva was chosen and all behavioral acts recorded continuously for 5 or more min. Behavioral acts were given a digital code, and the occurrence, duration of acts, and elapsed time were recorded on eight-channel paper tape by operation of a keyboard. The keyboard controlled a motorized paper-tape punch, and the perforated paper tape was computer-processed. Usually hundreds to thousands of larvae were present; thus a different larva was probably observed during each 5-min observation period and consequently each period was treated as an independent set of observations. A total of 447

¹ National Marine Fisheries Service, Southwest Fisheries Center, P.O. Box 271, La Jolla, CA 92037.

sets of observations was made of larvae ranging in age from 0 to 36 days.

Swimming and feeding behaviors were also recorded on motion picture film for subsequent

analysis. For cine photography the larvae were placed in round plastic containers 1 cm deep and 8 to 25 cm diameter which had black opaque walls and a transparent bottom. The tank was illuminated from above by a reflector flood lamp operated below rated voltage. A water bath was inserted between the lamp and the tank to prevent heating the water. Light from the lamp was focused with a fresnel lens on the lens of the motion picture camera beneath the tank. The camera arrangement and lighting system was similar to the one used by Baylor (1959) for photographing transparent organisms with infrared radiation. From the position of the camera the subject was silhouetted against an intensely bright background because the light was focused directly on the camera lens. Thus, low sensitivity, high resolution, and high contrast film could be used. Swimming and feeding larval anchovy were photographed with a high-speed camera at 128 fps (frames per second) using AHU microfilm manufactured by the Eastman Kodak Company.² Photographic analysis of feeding was restricted to larvae that fed on food particles 100 μ or larger in diameter because I was not able to resolve smaller food particles and still maintain the larvae in a reasonably large photographic environment. Much slower camera speeds—1 to 2 fps—were used to estimate swimming activity.

SWIMMING BEHAVIOR

CHANGES IN THE TYPE OF SWIMMING WITH DEVELOPMENT

During the first 2 days of larval existence, anchovy larvae exhibited little locomotor activity. Over 90% of the time they floated motionless in the water (Figure 1). Usually the head was directed downward and often the motionless yolk-sac larvae were transported slowly by water currents. Occasionally, they executed a brief but intense burst of swimming. These bursts of swimming, which I called continuous swimming, occurred about once a minute and lasted

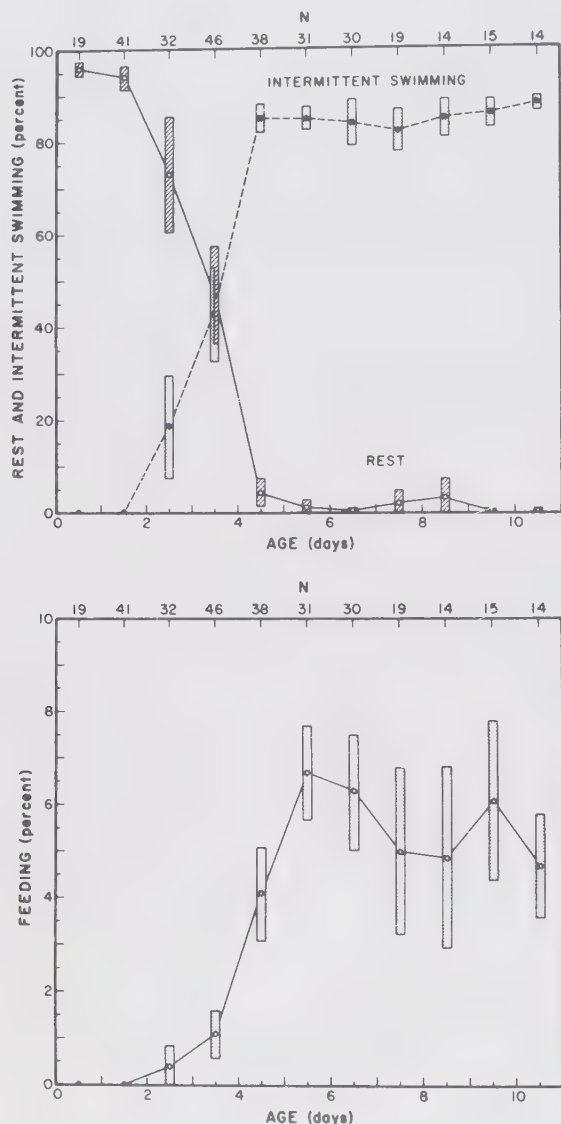


FIGURE 1.—Proportion of time spent in rest and intermittent swimming (top panel), and feeding (bottom panel) by anchovy larvae during the first 10 days of larval life. Points are mean percent $\pm 2 \times SE$, for each day; the number of observations (N) is given at top of graphs.

² Use of trade names does not imply endorsement by the National Marine Fisheries Service.

1 to 2 sec (Table 1). During a burst the tail and body beat continuously from side to side without interruption, and the larva accelerated and decelerated rapidly. Bursts of continuous swimming usually occurred in the absence of any observed stimulus although some bursts were stimulated by accidental contact with other larvae or the walls of the tank.

During the third day of larval life (age 2 days) a new swimming pattern appeared which was to become the dominant mode of locomotion throughout the rest of larval existence. The new mode of swimming was intermittent swimming, consisting of alternate periods of swimming and gliding; typically the larva executed one full tail beat, paused, and glided forward without beating the tail and then repeated the sequence of beating and gliding. The mean proportion of time devoted to intermittent swimming increased during the third and fourth days of larval life, more or less in proportion to the decrease in the time spent in rest (Figure 2). By the fifth day of larval life about 85% of the observation period was composed of intermittent swimming whereas the proportion of time devoted to rest during the day was nearly zero.

With the appearance of intermittent swimming the frequency and duration of continuous swimming decreased. Bursts of continuous swimming occurred once or twice per minute during the first 2 days of larval life whereas by the tenth day they occurred only once in 5 min, and the duration of the bursts also declined over the same period (Table 1). Bursts of contin-

TABLE 1.—Proportion of observation time spent in continuous swimming and the mean duration, and mean frequency, of bursts of continuous swimming during the first 10 days of anchovy larval life.

Age days	Percent of observation time Mean $\pm 2 \times$ SE	Frequency of bursts/min Mean $\pm 2 \times$ SE	Duration of bursts (sec) Mean $\pm 2 \times$ SE	N
0	2.4 $\pm$ 0.86	0.85 $\pm$ 0.28	1.86 $\pm$ 0.50	20
1	5.2 $\pm$ 0.99	1.72 $\pm$ 0.32	1.72 $\pm$ 0.48	32
2	2.0 $\pm$ 0.58	1.38 $\pm$ 0.22	1.38 $\pm$ 0.52	28
3	3.4 $\pm$ 0.24	0.76 $\pm$ 0.78	0.76 $\pm$ 0.22	45
4	0.7 $\pm$ 0.10	0.33 $\pm$ 0.06	0.33 $\pm$ 0.16	37
5	0.12 $\pm$ 0.16	0.11 $\pm$ 0.12	0.37 $\pm$ 0.54	32
6	0.16 $\pm$ 0.12	0.10 $\pm$ 0.22	0.31 $\pm$ 0.22	27
7	0.22 $\pm$ 0.16	0.18 $\pm$ 0.06	0.41 $\pm$ 0.26	11
8	0.15 $\pm$ 0.18	0.13 $\pm$ 0.12	0.23 $\pm$ 0.24	13
9	0.29 $\pm$ 0.20	0.29 $\pm$ 0.18	0.30 $\pm$ 0.16	15
10	0.10 $\pm$ 0.08	0.20 $\pm$ 0.08	0.22 $\pm$ 0.14	14

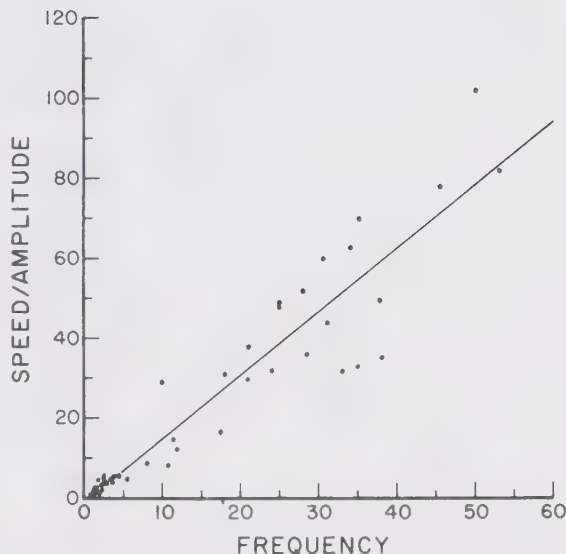


FIGURE 2.—Relationship between speed, tail beat frequency, and tail beat amplitude for anchovy larvae for all types of swimming. Equation for line is $V/A = -1.11 + 1.59 F$ where V/A is speed (cm/sec) divided by tail beat amplitude (cm), and F is tail beat frequency (beats/sec).

uous swimming occurred at a low frequency throughout the rest of larval life.

The appearance of intermittent swimming coincided with the appearance of feeding behavior. Feeding behavior was closely associated with intermittent swimming; food was sighted during intermittent swimming and the larvae advanced on the prey using this mode of locomotion.

POSSIBLE SIGNIFICANCE OF SPONTANEOUS BURSTS OF SWIMMING IN YOLK-SAC LARVAE

The regularity of the bursts of continuous swimming of yolk-sac larvae (age 0-1 day) suggests that the bursts may have a respiratory function. Yolk-sac larvae have no functional gill filaments, and oxygen must be obtained through the integument. Thus the regular bursts of continuous swimming could be necessary for gas exchange. I conducted a short experiment to test this hypothesis.

I measured the duration and frequency of bursts of swimming of age 0 day and 1 day larvae in open 10-liter containers containing water

saturated with oxygen and in ones containing water below saturation at 17°C. In the tests below saturation the initial level was 30% of saturation, but it increased to 65% by the end of the observation period 7 hr later.

At oxygen concentrations below saturation, larvae of both ages swam more frequently than did the controls of the same age ($P \leq 0.008$ Mann Whitney *U* Test, Siegel, 1956). Age 0 day larvae spent $5.36 \pm 1.41\%$ ($\pm 2 \times \text{SE}$, $N = 15$) of the time swimming in water below saturation whereas they spent $1.97 \pm 0.64\%$ ($N = 10$) of the time swimming at saturation. Age 1 day larvae spent $12.48 \pm 4.50\%$ ($N = 5$) of the time swimming in water below saturation whereas the controls spent $3.30 \pm 2.31\%$ ($N = 5$). The proportion of time spent swimming by the controls in both tests did not differ from that given in Table 1 for larvae of the same age.

This experiment suggests that the regular bursts of swimming of yolk-sac anchovy larvae have a respiratory function. On the other hand, the increase in swimming could have been the result of stress induced by low oxygen concentrations and bear no relationship to behavior under normal conditions. I am not inclined to accept this explanation because except for the increase in the duration and frequency of swimming, the behavior of the larvae was normal. A different motor pattern, vigorous shaking of the head, appears at lethal or near lethal levels of oxygen, about 12% of saturation at 17°C.

STRUCTURE OF CONTINUOUS AND INTERMITTENT SWIMMING

To estimate the relationship between larval anchovy tail movement, size, and speed during continuous and intermittent swimming, 53 film sequences were analyzed frame by frame. They included sequences of artificially stimulated and spontaneous bursts of continuous swimming and of bouts of intermittent swimming. In each swimming sequence the mean tail beat amplitude, swimming speed, and tail beat frequency were measured by use of a coordinate reader and digitizer (Hunter and Zweifel, 1971). I assumed that the net course swam was equivalent to a path formed from the midpoints of the tail beat. If the course was straight, this esti-

mate was the same as a regression of the *X* and *Y* coordinates for the positions occupied by the head or about the same as a straight line fit by eye through frame by frame tracings of the larva. If the course was curved, the path formed by the midpoints provided a reasonable estimate of the net curvilinear path followed by the larva.

Typically intermittent swimming could be separated from continuous swimming at a glance, but when the tail beat frequency approached that of continuous swimming it was difficult to distinguish between the two types of swimming. Thus, to separate all data into one of the two classes of swimming it was necessary to determine the beat frequency at which larvae changed from intermittent to continuous swimming. This was accomplished by measuring the elapsed time between beats in the slower swimming sequences.

When the tail was beat at a frequency of 4.7 beats/sec or higher, the movement of the tail was continuous, that is, the interval of rest between beats was equal to or less than 0.0078 sec (1 frame at 128 fps). At tail beat frequencies at or below 4.4 beats/sec the movement of the tail was not continuous but rather pauses of 0.086 to 0.811 sec existed between beats. The mean of the duration of rest between beats was 0.30 ± 0.22 sec ($\pm 2 \times \text{SE}$) whereas the duration of a single beat was 0.13 ± 0.05 sec. The duration of the pause or glide between beats was independent of larval size or swimming characteristics and was quite variable. The speed of tail movement was also independent of size but was about the same in all larvae. Thus, at beat frequencies below 4 beats/sec, larvae decreased speed by increasing the interval between beats but maintained about the same speed of tail movement.

Continuous and intermittent swimming data (Table 2) were analyzed separately to determine the relationship between tail beat amplitude, speed, length, and tail beat frequency. The general equation $V/A = a + bF$, where *A* is amplitude in cm, *F* is tail beat frequency, *V* is speed in cm/sec, and *s_i* is the standard deviation about the line, provided the best fit to continuous and intermittent data sets. The intercepts and slopes

for the two data sets were nearly the same, and consequently I combined the data and obtained the relationship of $V/A = -1.11 + 1.59F_{s_l} = 8.311$ for all data (Figure 2).

The principal difference between the above equation and ones derived by Bainbridge (1958) or by Hunter and Zweifel (1971) for adult fishes was that amplitude was the estimator of size instead of length. Amplitude was required in the present study because during bursts of continuous swimming larvae modulated the amplitude of their tail beat. Inclusion of length in addition to amplitude and frequency did not improve the relationship. In the study by Hunter and Zweifel (1971) fish did not modulate the amplitude of the tail beat because they swam at a steady speed. Amplitude is known to change during acceleration (Gray, 1968), and the behavior of larvae during bursts of continuous swimming was no exception to this rule.

During intermittent swimming, amplitude was not modulated but was maintained at a minimum value of about one-fifth of a body length. The relationship between amplitude and length

during intermittent swimming was obtained by the equation $A = 0.112 + 0.170 L$ where $s_l = 0.066$ (Figure 3).

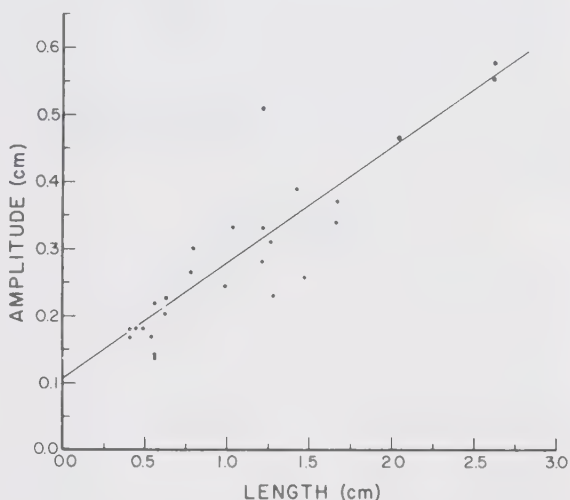


FIGURE 3.—Relationship between anchovy larval length (cm) and tail beat amplitude (cm) for intermittent swimming.

TABLE 2.—The speed, tail beat frequency, and tail beat amplitude for anchovy larvae of various lengths during continuous and intermittent swimming. Each value is a mean for a single swimming sequence swum by one larva.

Continuous swimming				Intermittent swimming			
Length	Speed	Tail beat frequency	Tail beat amplitude	Length	Speed	Tail beat frequency	Tail beat amplitude
cm	cm/sec	beats/sec	cm	cm	cm/sec	beats/sec	cm
0.34	4.71	38.1	0.133	0.41	0.31	2.3	0.169
0.37	4.59	33.3	0.142	0.41	0.30	2.0	0.182
0.38	0.75	5.5	0.143	0.45	0.33	2.4	0.183
0.39	10.68	45.5	0.137	0.49	0.20	2.3	0.181
0.41	1.22	10.9	0.150	0.54	0.64	3.8	0.170
0.42	1.08	4.7	0.194	0.56	0.44	2.1	0.221
0.42	8.05	35.3	0.115	0.57	0.73	4.5	0.138
0.42	11.63	50.0	0.114	0.57	0.37	2.7	0.142
0.42	3.86	17.9	0.124	0.62	0.17	1.1	0.205
0.43	7.28	30.5	0.121	0.63	1.01	2.8	0.229
0.43	8.92	34.5	0.140	0.78	0.63	1.3	0.267
0.43	7.91	28.2	0.152	0.79	0.52	1.5	0.302
0.43	7.48	38.5	0.147	0.98	0.20	1.4	0.245
0.44	12.18	53.3	0.148	1.03	1.61	3.1	0.333
0.44	4.89	35.3	0.148	1.21	1.23	2.8	0.514
0.50	9.61	24.7	0.200	1.21	1.35	2.3	0.278
0.56	2.52	17.5	0.150	1.21	1.52	2.6	0.332
0.72	1.75	8.0	0.206	1.27	1.18	2.7	0.310
0.72	2.17	11.4	0.150	1.28	1.27	2.6	0.231
0.93	4.28	10.2	0.148	1.42	1.02	2.1	0.390
1.00	11.22	28.6	0.311	1.47	1.26	3.2	0.257
1.00	15.91	20.7	0.422	1.66	1.02	1.7	0.340
1.24	31.26	31.6	0.716	1.66	0.78	1.7	0.372
1.24	9.08	12.0	0.718	2.04	1.68	2.2	0.468
1.24	23.16	21.0	0.777	2.62	2.50	1.9	0.581
1.32	21.16	24.0	0.664	2.62	3.02	2.9	0.555
1.42	26.85	25.0	0.545				

At intermittent swimming speeds tail movement was slow enough that the frequency of the beat could be counted by eye. If the length of the larva were known, intermittent swimming speed could be estimated from the general speed equation given above, the amplitude equation for intermittent speeds, and the tail beat frequency. Instead of the general speed equation it may be preferable to use one based on intermittent swimming data alone, which is $V/A = 0.0466 + 1.308 F$ where $s_t = 1.160$.

BURST SPEEDS

The speeds obtained by larval anchovy during bursts of fast continuous swimming are of interest because they may be a measure of the larva's ability to avoid predators or possibly plankton nets. Bursts of fast swimming were stimulated in larvae of mean length 4.1 ± 0.1 mm (Table 2, continuous swimming, 0.34 to 0.44 cm larvae) and mean length 12.1 ± 1.2 mm (Table 2, continuous swimming, 1.00 to 1.42 cm). Bursts were stimulated by moving a pin near a larva and photographing the larva at the film speed of 200 fps. Speeds were averaged for the entire duration of the burst, which lasted about 0.1 to 0.2 sec. The stimulated burst speed for larvae of mean length 4.1 mm was 63 ± 19 mm/sec (mean $\pm 2 \times$ SE) or about 15 body lengths/sec and that for the 12.1-mm larvae was $198 \pm$ mm/sec or about 16 body lengths/sec. The maximum speed obtained by larvae in the 4.1 mm length class was swum by a 4.2-mm larva which swam 116 mm/sec (28 body lengths/sec) during a burst of 0.12 sec. The maximum speed for larvae in the 12.1 mm class was 313 mm/sec (25 body lengths/sec) swum by a 12.4-mm larva during a burst lasting 0.10 sec. In summary, larvae had a maximum speed capability of 25 body lengths/sec or faster for bursts lasting 0.1 to 0.2 sec, but the typical or average burst speeds were close to 15 body lengths/sec.

ESTIMATES OF DAILY RATE OF SWIMMING

I shall consider only intermittent swimming in the estimates of daily swimming rate because only intermittent swimming was associated with food search, and because once feeding began,

continuous swimming was an insignificant proportion of daily activity (Figure 1 and Table 1). Two independent methods were used to estimate the rate of intermittent swimming. In the first method, larvae were photographed at 2 fps in a cylindrical chamber of 25 cm diameter, and swimming speed calculated from frame-by-frame analysis of the photographs. Five minutes of swimming were analyzed for each larva; swimming was divided into intermittent and continuous types; and periods of inactivity equal to or greater than 5 sec were tabulated as rest. In the second method, visual observations of larvae in the 500-liter rearing tanks were used to record the tail beat frequency of larvae during intermittent swimming and the frequency and duration of continuous swimming and rest. Larvae were observed three or more times a day. The speed of larvae during intermittent swimming was calculated from the tail beat frequency by use of the relationships between age, length, amplitude, tail beat frequency, and speed previously described.

The speed of intermittent swimming measured from photographs increased with larval length (Figure 4), and the regression of speed on length gave the relationship $V = -0.215 + 1.038 L$ where $s_t = 0.280$. Visual measurements of tail beat frequency of intermittent swimming

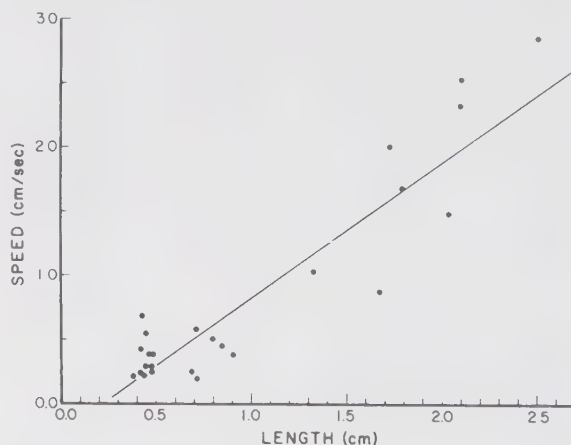


FIGURE 4.—Rate of movement during intermittent swimming (cm/sec) as a function of anchovy larval length (cm). Measurements taken from analysis of cine photographs. Equation for line is $V = -0.215 + 1.038L$.

TABLE 3.—Comparison of visual and photographic estimates of speed of intermittent swimming for anchovy larvae of three sizes.

Larval length (cm)	Tail beat amplitude ¹ (cm)	Intermittent speed estimates (cm/sec)		Distance traveled ⁴ (m/hr)	
		Visual ²	Photographic ³	Visual	Photographic
0.5	0.197	0.414	0.304	12.3	9.0
1.0	0.282	0.592	0.823	17.6	24.5
1.5	0.367	0.771	1.342	22.9	39.9

¹ Estimated from $A = 0.112 + 0.170L$.² Estimated from $V/A = 0.047 + 1.308F$, where $F = 1.57$.³ Estimated from $V = -0.215 + 1.038L$.⁴ When 82.6% time spent swimming.

did not change with age over the first 30 days of larval life. That tail beat frequency did not change implied that the interval of rest between beats, the principal determinant of frequency, was dependent on variables unrelated to size or development. The same conclusion was obtained from analysis of the structure of intermittent swimming in the preceding section. Thus, the change in speed associated with increased length or age may be a function of only the increase in tail beat amplitude with length.

The mean tail beat frequency for intermittent swimming, 1.57 ± 0.03 beats/sec, was substituted into the speed equation for intermittent swimming. Speed of intermittent swimming could then be determined for larvae of any length by substitution of the appropriate tail beat amplitude into the equation. Speed estimates in which the above procedure was used and ones based on photographic analysis are compared in Table 3. The two sets of estimates are reasonably close for 0.5-cm larvae but they diverge for larger ones. No reason exists to disregard either set of estimates. It seems reasonable to assume that the true values lie somewhere between them.

The proportion of daylight hours devoted to intermittent swimming must be considered to estimate the distance traveled per hour. Visual observations are preferable for this purpose because of the greater number of observations (318) and because visual observations were systematically taken at different times of day. Between ages 4 and 30 days, no trend with age existed in the proportion of time devoted to swimming although time spent swimming decreased slightly on days of intensive feeding.

The mean proportion of time devoted to intermittent swimming was $82.6 \pm 1.2\%$. To arrive at this estimate I considered periods of inactivity longer than 5 sec as rest and periods equal to or less than 5 sec as a part of intermittent swimming bouts. Estimates of the distance traveled per hour, assuming 82.6% of the time is spent swimming, are shown in Table 3. These values will be combined with others to estimate rate of food search in a later section.

FEEDING BEHAVIOR

DESCRIPTION OF FEEDING BEHAVIOR

After a larva sighted a prey, the head turned toward it so that the prey was perpendicular to the tip of the snout and thus in about the center of the binocular field of the larva. Then, while keeping the prey in the center of the binocular field, the larva swam slowly toward the prey by executing one or more tail beats. After swimming ceased, the larva contracted its body into an S-shaped striking posture typical of the larval clupeoid fishes (Figure 5). During contraction of the body, the prey was maintained directly in front of the snout and small movements by the prey were compensated for by slight adjustments in the orientation of the head and larger movements by rotating the entire body with the pectoral fins. The larva continuously moved toward the prey while forming the strike posture by high frequency (50 to 60 beats/sec), low amplitude vibration of the finfold or caudal fin.

The order and rate at which portions of the body were contracted to form the S-strike posture were not fixed. The order appeared to be related to the initial orientation of the head and trunk. Frequently swimming movements were integrated into the beginning of the strike posture. The larva while approaching a prey often ceased swimming with the body partially bent, and the contractions to form the strike posture were carried onward from that point. Variations in the rate of contraction were related to movements of the prey. If the larva did not keep up with a moving prey, contraction of the body was often interrupted and the incomplete posture held for an extended period. The ampli-

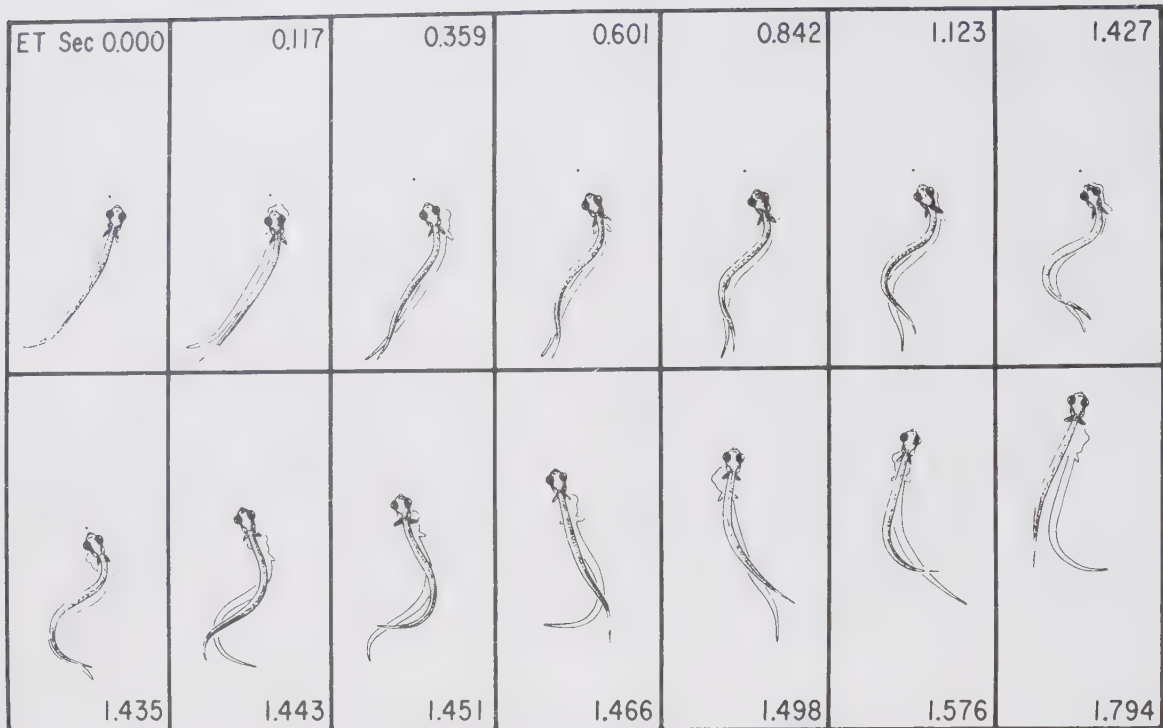


FIGURE 5.—Tracings of selected motion picture frames from a feeding sequence of an anchovy larva (8.9 mm, 21 days old) and a prey taken at 128 frames per second. Frame lines are fixed such that distance moved by larva is indicated by comparison of tracings; and unshaded image indicates position of larva in the preceding tracing. The following events are illustrated: elapsed time (ET) 0 sec, larva sights prey; ET 0-0.117 sec, larva orients head toward prey and swims toward it; ET 0.117-1.435 sec, larva forms s-shaped strike posture; ET 1.435-1.443 sec, strike begins and prey captured; and ET 1.451-1.794 sec, forward movement continues as tail returns to axis of progression.

tude of the posterior bend in the body reached a maximum just before the strike was begun.

The larva began the strike by drawing the tip of the tail rapidly anteriorly. It then thrust the tail backward, extended the head, opened the mouth, and the particle was taken or missed within 7.8 to 15.6 msec after the beginning of the backward thrust of the tail (one to two frames at 128 fps). The entire feeding sequence from sighting the prey to the strike lasted only 1 to 2 sec. The sequence of movements were so rapid that my first impression was that they were extremely stereotyped. Later, frame-by-frame analysis of film taken at 128 fps indicated that normal variance was associated with every characteristic that could be measured in the films.

Larvae of 15 to 20 mm formed the strike posture in less time than did one 5 to 15 mm long, and consequently, feeding sequences were shorter in larger larvae (Figure 6). On the other hand, the time used to approach the prey before forming the strike posture was about 0.6 sec in larvae of all sizes. Other characteristics increased directly in proportion to length, for example, the maximum amplitude of the body in the strike posture, the distance to the prey at the time of the strike, and the rate of movement toward the prey while in the strike posture. The speed of the strike also increased with length but the relationship appears to be nonlinear. The speed of the strike relative to length was less in the largest size class of larvae.

INCOMPLETE FEEDING SEQUENCES

Feeding sequences often ended before they were completed by execution of the strike. The mean frequency of feeding strikes (the last act in the feeding sequence) for all visual observations for larvae of ages 4 to 27 days was 1.28 ± 0.14 strikes/min ($N = 325$) whereas that for the orientation movement of the head (the first act in the sequence) was 3.22 ± 0.30 . Thus, about 40% of all feeding sequences were completed. The proportion of feeding sequences that were completed did not change with age, but there was some indication that the proportion of incomplete sequences increased when the larvae began to feed on *Artemia* nauplii. This increase in the proportion of incomplete sequences was caused by an increase in the proportion of sequences ended at the first act, the orientation movement of the head. The proportion of feeding sequences that were carried as far as bending the body was 52% and remained about the same regardless of age or food type.

In the film analysis I analyzed only incomplete feeding sequences that were continued beyond the head orientation movement and compared them with completed sequences. These measurements indicated that some feeding sequences ended at every stage up to and including the final strike posture, and the duration of incomplete sequences overlapped that of completed ones (Table 4). The only characteristic measured in the photographs that consistently separated incomplete from completed feeding sequences was that at the end of incomplete ones the prey was farther away from the larvae than it was in completed sequences. Thus, the principal cause

of the failure to continue a feeding sequence was an inability to closely approach the prey while forming the strike posture.

To summarize, photographic analysis of incomplete and complete feeding sequences indi-

TABLE 4.—Comparison of characteristics of incomplete and complete feeding sequences for larval anchovy 5.1-10.0 mm.

Characteristic	Incomplete sequence ¹ Mean $\pm 2 \times$ SE	Complete sequence ² Mean $\pm 2 \times$ SE
Duration of S-posture (sec)	0.82 ± 0.26	1.11 ± 0.16
Duration entire sequence (sec)	1.38 ± 0.40	1.71 ± 0.26
Body amplitude (mm)	1.03 ± 0.40	1.52 ± 0.20
Distance to prey at end of sequence (mm)	0.81 ± 0.17	0.41 ± 0.04
S-posture forward movement (mm/sec)	0.51 ± 0.26	0.80 ± 0.34

¹ $N = 19$.

² $N = 13$.

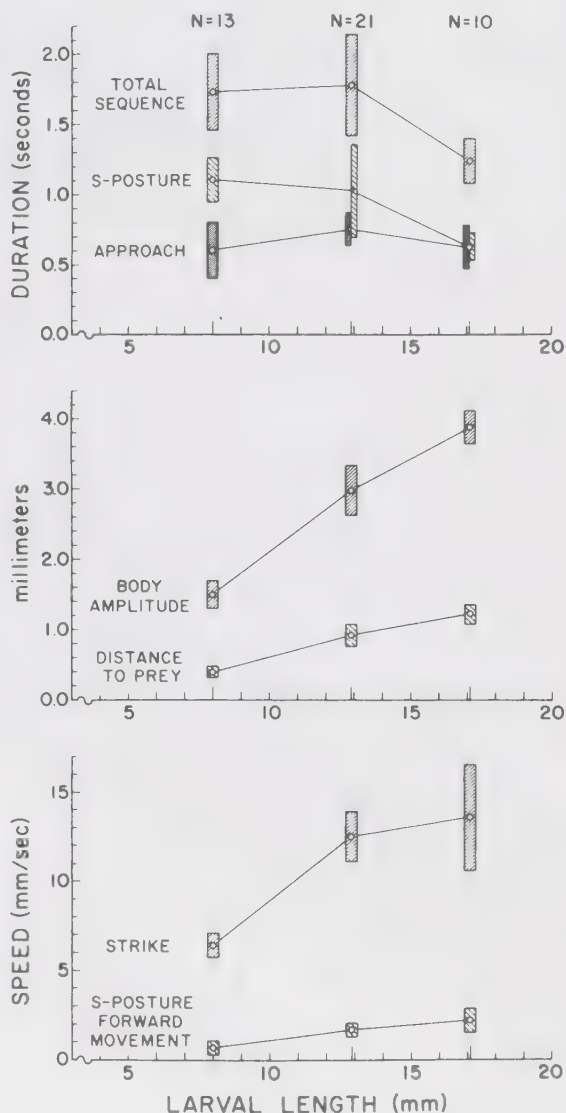


FIGURE 6.—Characteristics of complete feeding sequences of anchovy larvae taken from film analysis. Values are means $\pm 2 \times$ SE for three size classes of larvae (5.1-10.0, 10.1-15.0, and 15.1-20.0) and are plotted at the mean length of the larvae in the class.



FIGURE 7.—Reactive perceptive field in the horizontal plane for anchovy larvae. Each point represents position of a prey in the horizontal plane at time larvae first reacted to it. Distances in X and Y axes were divided by the lengths of the larvae and expressed as proportions of larval length. Arrows indicate lines that would enclose 95% of prey sighted in each plane.

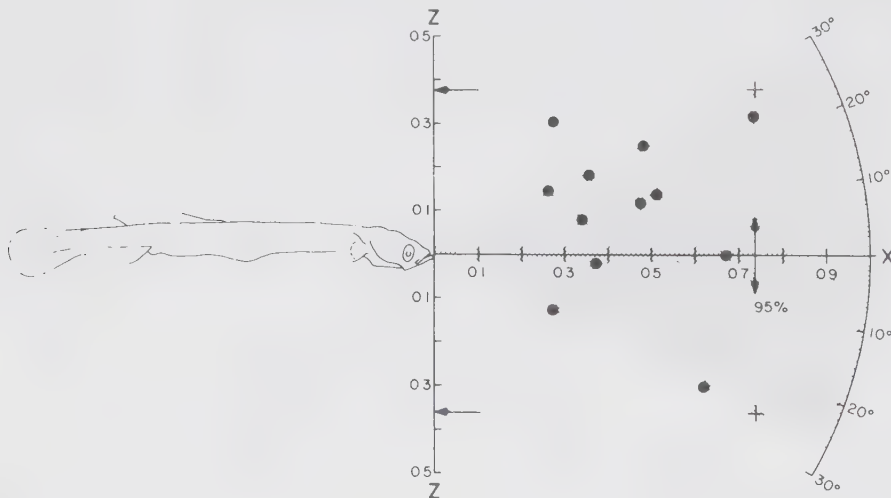


FIGURE 8.—Reactive perceptive field in the vertical plane for anchovy larvae. Distances on X and Z are expressed as a proportion of larvae length; points are position of prey when larvae first reacted to them; crosses indicate point of intersection of visual cone with $Y = 95\%$ (the 95% limit of prey distribution in Y given in Figure 7); and arrows on Z indicate projected values of Z for intersection points.

cated that considerable flexibility exists in what appeared to be a highly stereotyped feeding pattern. Although a sequence was completed in only 1 to 2 sec, the larvae depend on feedback from the prey throughout the period. The larvae respond to the prey during the sequence by adjusting posture, speed, and direction of movement and by ending or continuing the sequence.

EXTENT OF REACTIVE PERCEPTIVE FIELD

The size of the predator's reactive perceptive field (Holling, 1965) is an essential element in the estimation of the rate of search for prey by a predator, that is, the extent of the area in which a predator will react to a prey. In studies on larval fishes the cross-sectional area of the perceptual field is multiplied by the speed of swimming to estimate the volume of water searched per unit of time. Estimates of this type have been made by Braum (1967), Rosenthal and Hempel (1970), and Blaxter (1966) and are summarized by Blaxter (1969).

To determine the position of prey when larvae first reacted to them feeding, larvae were filmed from below for horizontal measurements and separately from the side for measurements in the vertical plane. Seventy-one horizontal film sequences of larvae, 4.0 to 24.2-mm, and 12 vertical sequences of larvae, 7.0 to 24.7 mm, were analyzed frame by frame.

In the film analysis all measurements were made in reference to the body of the larvae; X signified measurements made in the axis of progression or swimming plane; Y those in the other horizontal axis; and Z those made along the vertical axis. Vertical measurements were made in relation to the orientation of the larvae and were not necessarily vertical in relation to the water surface. Searching behavior was independent of body orientation. Larvae reacted to prey when they swam upward, when they swam downward, as well as when they swam parallel to the water surface.

In each photographic sequence the angle and distance of the prey from the tip of the snout of the larva were measured 15 msec before the larva reacted to the prey by turning the head toward it (two frames at 128 fps). To correct for obvious length-dependent differences in field

size the distance to the prey was divided by laryal length and was expressed in body lengths (L). Prey organisms included *Brachionus*, various veliger larvae, *Artemia* nauplii, and wild copepod nauplii of undetermined species.

In the horizontal plane larvae reacted only to prey ahead of them; prey at 90° or more from the tip of the snout were not selected, and most prey were less than 60° from the snout (Figure 7). The reactive perceptive field in horizontal cross section was roughly circular. A circle of radius $0.4L$ with the center on the axis of progression or X axis enclosed 90% of all prey sighted (shaded area, Figure 7). In the vertical plane, larvae reacted to prey below as well as above the X axis. The maximum distance above and below the X axis at which prey were sighted in the vertical plane was $0.3L$ and thus the maximum extent of Z was $0.6L$ (Figure 8). The reactive perceptive field may be roughly triangular in vertical cross section, because a triangle with a central angle of 53° and altitude of $0.74L$ enclosed all but one of the 12 observed values.

Maxima seem appropriate rather than averages to estimate the extent of the reactive perceptive field because only the exceptional larva survives in nature and because field size may change with feeding motivation. Considering the two axes in the horizontal plane separately, for 95% of all prey sighted the value Y for the position of prey was equal to or less than $0.4L$ from the axis of progression (X axis), and for 95% of all prey the X values for prey position were equal to or less than $0.74L$. Ninety-five percent limits could not be used to estimate Z because the observations were too few to calculate percentages. The maximum observed Z value above and below the X axis was $0.3L$. This value could be used or alternatively Z could be estimated at a point on X by assuming the field is triangular in cross section as illustrated in Figure 8. Using the 95% limit for X , $0.74L$, as the point to make the cross section, we obtain an estimate of $Z = 0.36L$. Thus, the estimate of the maximum extent of Z varied from 0.30 to $0.36L$ depending on the assumptions used. Assuming an elliptical cross section where $Y : 0.40L$ and $Z = 0.36L$ the area of the ellipse is

equal to $0.45L^2$ for a cross section at $X = 0.74L$. To estimate the volume search per unit time these areas need to be multiplied by the larval swimming speed. This aspect of the calculation will be considered in a subsequent section.

FEEDING RATES

In all studies in this paper larvae were observed and maintained in tanks containing high and presumably optimum food densities (*Gymnodinium* 100 to 200/ml, *Brachionus* 10 to 20/ml, and *Artemia* nauplii 3 to 10/ml). It is unlikely that density limited the rate of feeding under these conditions. Thus, the rates recorded probably are near the maximum feeding rate that can be sustained by larval anchovy.

Records were kept of the frequency of feeding acts of larvae ages 4 to 27 days raised in the 500-liter rearing tanks. A total of 325 observations of 5-min duration was taken at three different times of day. No trend in the frequency of feeding strikes with time of day existed. The larvae fed actively throughout the day although their guts were filled after the first half hour of feeding each morning. The average frequency of feeding strikes for all data combined was 1.28 ± 0.144 strikes/min. Some evidence existed that the rate may climb to 3 strikes/min for 2 to 3 days when *Artemia* nauplii were first introduced, but no direct cause and effect relationship could be established because other prey were also present in the tank.

Another estimate of feeding rate was obtained from the data on feeding success described in the next section. The larvae in that study had empty guts at the beginning of the observation period, and they were observed during their initial 10 min of feeding on a particular day, whereas the preceding data observations were begun about a half an hour after the larvae began feeding and continued throughout the day. The average feeding frequency for larvae studied in the feeding success experiments ($N = 100$) was 1.75 ± 0.205 strikes/min and the range was from 0.2 to 5.8 strikes/min. Thus, during the first 10 min of feeding, feeding rates were on the average somewhat higher than they were when averaged over the entire day. Feeding rates on *Artemia* were the same as those on *Brachionus*.

FEEDING SUCCESS

Feeding success was estimated by counting the number of feeding acts completed in 10 min, removing the larvae from the container, and counting the number of prey in the gut. Larvae were kept in the dark for 12 or more hr before the test to insure that the gut was empty (anchovy larvae do not feed in the dark). I measured the feeding success of larvae fed *Brachionus* (density, 10 to 60/ml) from the first day of feeding (age 3 to 4 days) up to the 21st day of larval life. A separate experiment was run to determine the effect of a different prey on feeding success. At age 17 days the diets of some of the larvae were changed from one of only *Brachionus* to one of *Artemia* nauplii (density, 3 to 15/ml). Measurements of feeding success were made over the first week of feeding on *Artemia*. *Gymnodinium* was not used as a food for first feeding larvae because it was usually defecated before we were able to examine the contents of the gut. Two measurements of feeding success of larvae fed *Gymnodinium* fell within the scatter for *Brachionus* (Figure 9).

The success of larvae fed *Brachionus* rapidly increased over the first week of feeding (age 3 to 10 days), but thereafter the rate of increase of feeding success was much lower. The form of the relationship between age and success was that of a learning curve. A semilog transformation of the data provided an adequate correction for this curvilinear trend. The regression of feeding success in percent on the log of larval age gave the relationship, percent success = $93.2 (\log \text{ age}) - 33.30$ where $s_1 = 20.14$.

Seventeen-day-old larvae were less successful in capturing *Artemia* for the first time than they had been in capturing *Brachionus*. Only 37% of feeding acts were successful when larvae were fed *Artemia* nauplii for the first time at age 17 days whereas 81% were successful when the food was *Brachionus* (Figure 10). The initial level of feeding success for larvae fed *Artemia* was higher than that of larvae when they first began to feed at age 3 to 4 days, and less time was required to obtain a high level of success on *Artemia* than was required for first feeding larvae. By the third day of feeding on *Artemia*

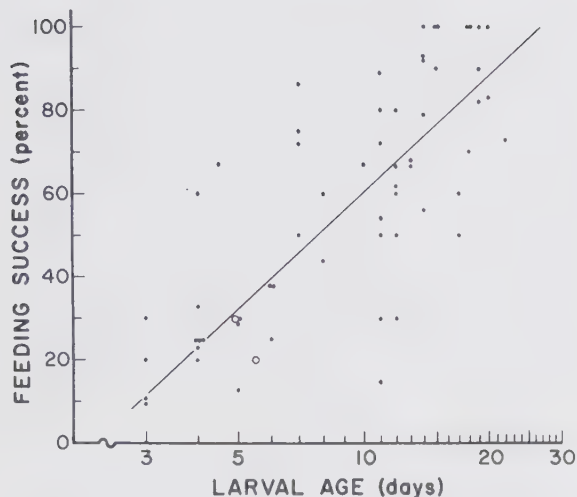


FIGURE 9.—Feeding success (percent of prey captured) of anchovy larvae of various ages fed *Brachionus*. Larval age is plotted on log scale, equation for line is percent success = $93.2(\log \text{ age}) - 33.30$. Two open circles, larvae fed *Gymnodinium*.

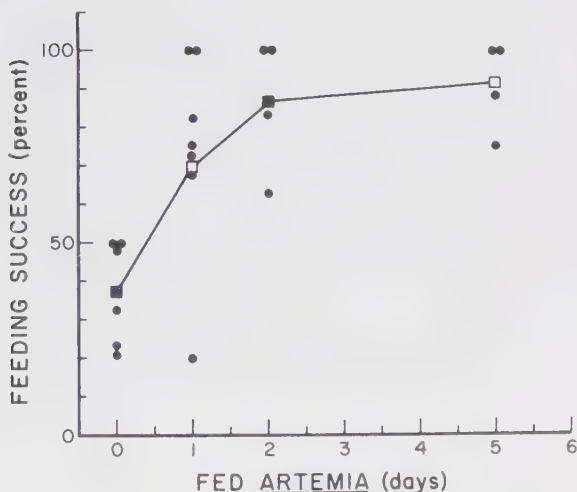


FIGURE 10.—Feeding success of anchovy larvae fed *Artemia* for the first time at age 17 days (0 days on abscissa) and for 5 additional days. The line connects mean values.

the level of success had reached the same level as it had after 2 weeks of feeding on *Brachionus*.

One interpretation of these results is that a considerable proportion of feeding experience on

one type of prey is transferable when larvae feed on a new prey. On the other hand, the surprisingly long period (about 2 weeks) required to achieve a high level of feeding success on *Brachionus* suggests that maturation of sensory and locomotor systems may also play a role in anchovy larval feeding behavior during the first 2 weeks of larval life.

ESTIMATION OF VOLUME SEARCHED

In this section I combine the estimates made in the previous section to estimate the volume of water searched by larvae per hour and will use this estimate and others in a subsequent section to calculate the density of food required by larvae to meet metabolic requirements.

The volume of water searched per hour by larvae was calculated by multiplying the cross-sectional area of the reactive perceptive field by the distance traveled per hour by larvae. I made separate calculations for the photographic and the visual speed estimates given in Table 3. In both calculations the speed estimates were adjusted for the proportion of time spent swimming, 82.6%, and they were extended from distance/sec to distance/hr. In this and all subsequent calculations I have made larval age and length interchangeable by using the growth equation $l_t = 3.24e^{0.055t}$ given by Kramer and Zweifel (1970) who reared anchovy larvae at 17°C under conditions similar to those used in this study.

The estimate of the volume of water searched per hour increased exponentially with size (Figure 11). The two volume estimates were close for larvae less than 10 mm long but they diverged for larger ones. There was no reason to select one estimate over the other and, consequently, I chose to use the average of the two for future calculations. When the two estimates are averaged the outcome is nearly the same as the relationship, volume searched/hr = $1,000L^3$, where L is larval length in cm and volume is in cm^3 , or simply, liters searched/hr = L^3 . Examination of Figure 11 shows the line for L^3 falls almost midway between the two estimates. I shall use the average estimate in the rest of the calculations, but L^3 could be used with only a negligible difference. In the larger larvae L^3

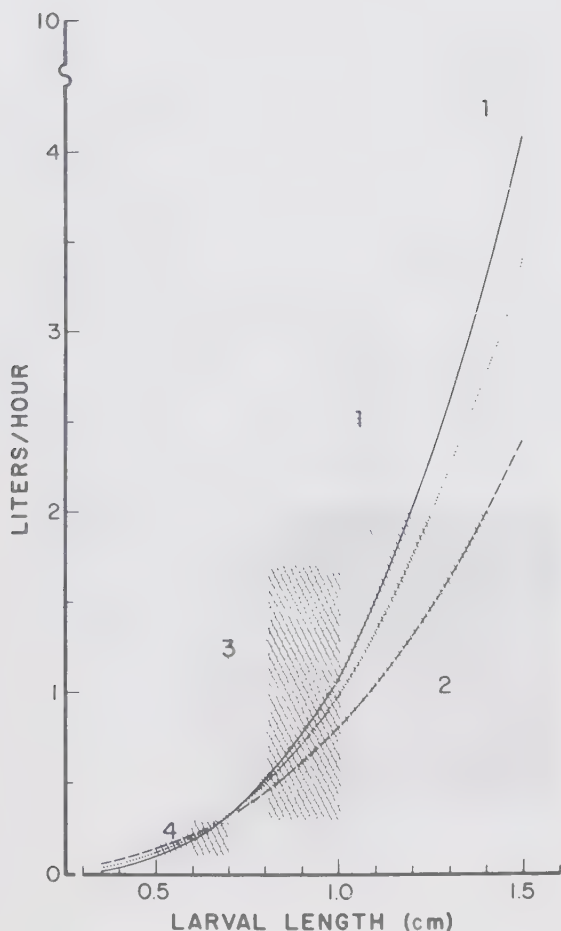


FIGURE 11.—Estimates of liters/hour searched by anchovy larvae 0.3-1.3 cm total length. Lines are based on average estimates and are not data points. Solid line is the volume searched when the photographic estimate of swimming activity was used; dashed line, the volume searched when visual estimate of swimming activity was used; and dotted line, the relationship, liters/hour = L^3 , where L is total larval length (cm). Rectangles enclose estimates of search rates for other larval fishes from the literature: 1) *Clupea* (Rosenthal and Hempel, 1970); 2) *Clupea* (Blaxter, 1969); 3) *Pleuronectes* (Blaxter, 1969); and 4) *Sardina* (Blaxter, 1969).

yields a slightly higher estimate than the average estimate, but the difference does not exceed 5% even in the largest larva under consideration.

That the change in volume searched with length was nearly proportional to L^3 could be

expected. The volume is the product of the speed and cross-sectional area of the perceptive field for prey. I assumed a length coefficient of one in the calculation of cross-sectional area (area = $0.45L^2$), and the length coefficients for the two swimming speed estimates were close to one as is commonly the case in swimming speed studies (Bainbridge, 1958; Hunter and Zweifel, 1971). Thus the product of the length coefficient for speed and the one for area would be expected to be close to L^3 . On the other hand, that the product of the various constants used in the calculation was close to 1,000 was simply chance.

The estimates of volume searched made for other larval fishes, shown as rectangles in the figure, are close to the two for anchovy, especially when the variance in such estimates is considered. How much of the difference between anchovy and other species can be attributed to specific differences and how much to differences in technique and assumptions is unknown. For example, differences in techniques of estimation of the distance of prey at the time of sighting could account for the differences between my results and others. The initial movement of the head toward the prey was easily detected in the films, but it is possible that a significant period elapsed between recognition and movement of the head. If this is true, I have underestimated the size of the perceptive field for prey. Perhaps some of the herring estimates are higher than the anchovy because the anchovy swims more slowly. Anchovy swim more slowly because unlike most pelagic fishes the anchovy swims intermittently; that is they glide between beats of the tail.

ESTIMATION OF FOOD DENSITY

To fulfill their metabolic requirement larval anchovy must ingest about 686 rotifers/day/mg dry weight or the caloric equivalent. This estimate was derived from the following: 4.5 μ liter of O_2 /mg dry wt/hr is consumed by anchovy larvae kept on a 14-10 hr light-dark cycle (Lasker, personal communication); 1 μ liter O_2 = 0.005 cal; caloric value of the rotifer (*Brachionus*) = $5,335 \pm 139$ cal/g (Theilacker and Mc-

Master, 1971); dry weight 1 rotifer = $0.16 \mu\text{g}$ of which 92.2% is organic material (Theilacker and McMaster, 1971); and the assumption of 100% digestive efficiency. The estimate was converted from unit weight to length by the length-dry weight relationship of $\log W = 3.3237 \log L - 3.8205$ given by Lasker et al. (1970).

The metabolic requirement given above was adjusted for feeding success by increasing it in proportion to the number of prey missed during feeding as predicted by the feeding success equation presented previously. The density of food required for survival was estimated by dividing the food requirement adjusted for feeding success by the volume of water searched in 10 hr. The average of the photographic and visual estimates of volume searched was used to calculate the volume searched by larvae. A 10-hr feeding period was chosen purely as a convenience because the actual duration of daily feeding periods is unknown.

The density of rotifers required to meet metabolic requirements decreased exponentially with size (Figure 12). First feeding larvae, 3 days old (3.5 mm) require 105 rotifers or the caloric equivalents/liter during a 10-hr feeding period whereas 10-day-old larvae (5.9 mm) require only 34 rotifers/liter. Older larvae require much lower food densities primarily because feeding success increases exponentially with age.

Density estimates based on rotifer equivalents probably underestimate the prey density required during the first few days of feeding because a smaller prey is needed by most anchovy larvae during this time. For example, Theilacker and McMaster (1971) found that only 12% of anchovy larvae survive to 19 days old when *Brachionus* was the only food, whereas 40 to 50% survived if in addition to *Brachionus* the dinoflagellate, *Gymnodinium*, was present during the first few days of feeding. To obtain a better estimate of food density required by larvae during the first days of feeding I estimated the caloric value of a single *Gymnodinium* cell and recalculated the density required in terms of dinoflagellate equivalents. The caloric value of a single *Gymnodinium* cell was estimated from the carbon content (Mullin and Brooks, 1970) and by assuming that the carbon content

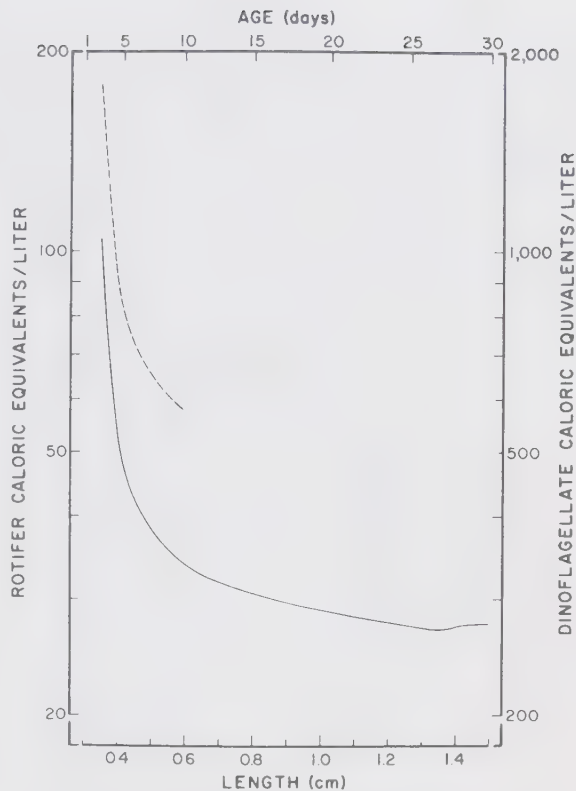


FIGURE 12.—Estimate of the density of prey in rotifer caloric equivalents/liter (left ordinate, solid line) and in dinoflagellate equivalents (right ordinate, dashed line) required to meet metabolic requirements of larval anchovy of 0.3-1.5 cm. Lines are based on average estimates. The shapes of the two curves are the same, but they differ in elevation by a constant factor of 17.

represented 40% of the organic material and that the caloric value of *Gymnodinium* was 5,000 cal/g of organic material. According to this calculation the caloric value of a single *Brachionus* is about 17 times that of a single *Gymnodinium* cell. Thus larvae feeding on dinoflagellates require about 17 times the prey density (dashed line Figure 12) than do those feeding on rotifers (solid line). Nearly all larvae are able to feed on *Brachionus* by age 5 days; thus, the food density requirement for the majority of the larvae shifts from 1,790 dinoflagellates/liter at age 3 days (the first day of feeding) to 48 rotifer equivalents/liter at age 5 days.

Although there are some differences, most of the assumptions and procedures I used were similar to those used by Rosenthal and Hempel (1970) to estimate food densities required by herring larvae. Rosenthal and Hempel estimated that the minimum food ration for herring larvae 10 to 11 mm was 4 to 8 nauplii/liter and the maximum was 21 to 42/liter. My minimum estimate based on metabolic considerations for a comparable size anchovy larvae was 29/liter. For the minimum density they assumed, as I have, that the larva struck at all prey that entered its perceptive field, but for the maximum density they assumed that only a part of the plankters perceived resulted in a completed feeding sequence. In the anchovy larvae feeding on food at high density, on the average only 40% of feeding sequences were completed. Thus, using a similar criterion for a maximum ration as Rosenthal and Hempel (1970), the maximum density required for anchovy larvae would be 2.5 times the minimum ration or for a 10- to 11-mm larva about 72 rotifer equivalents/liter. Considering specific differences and the differences in assumptions and procedures, the estimated food requirements of herring larvae by Rosenthal and Hempel (1970) do not differ much from the one calculated for an anchovy larva of comparable size.

In a survey of the literature given by Blaxter (1965) the densities of food for larval clupeoid fishes in the natural environment ranged from 1 to 68 items/liter. Arthur (1956) in a comprehensive study of the food of pelagic larvae in the California Current region found 1 or more nauplii/liter in 72% of his samples and 30 or more nauplii/liter in about 3% of his samples. Beers and Stewart (1967) measured the density of copepod and naupliar and post naupliar stages (35 to 103 μ) in a 600-mile transect in an area of anchovy abundance and obtained densities ranging from 5 to 17 copepods/liter. Thus, food in the natural environment appears to be near or below the minimum concentration I estimated was required for older larvae but considerably below that for first feeding larvae.

Nearly every adjustment that could be made in my estimates of food requirements for anchovy larvae would sharpen the differences be-

tween early and late larval stages or elevate the overall food requirement. For example, natural prey would be of greater variety and could be more difficult to capture, thus causing a differential increase in food concentration required by younger larvae. In addition, older larvae are capable of feeding on a greater variety of food because they can feed on all food used by younger stages plus larger prey as well. I assumed a digestion efficiency of 100% but it must be less than that and this would also increase the overall food requirement. In short, an adjustment in the estimates would probably increase the difference between the estimated food density requirements taken from laboratory measurements and natural food densities.

Laboratory measurements indicated that larval anchovies are more vulnerable to death from starvation just after yolk absorption than at any other time during larval life. This conclusion agrees with those drawn from similar laboratory studies on the herring and other species. Whether or not the increased vulnerability to a starvation death just after yolk absorption is related to year class strength as contended by Hjort (1914) is still a debated question (Blaxter, 1969; Saville, 1971). The catch curves for larval anchovy over 10 years give no indication of an increase in mortality just after yolk absorption (Lenarz, 1972). Three explanations for the absence in the anchovy of an early critical period are: first, turbulence may generate random movement between fish larvae and prey and thereby considerably extend the search volume (Murphy, 1961); second, it may be that the mortality of larvae at all stages is so great because of starvation and other causes that the increased vulnerability at the youngest stages is not detectable; and third, food may not be limiting for early larvae because of patchy food distribution. The absolute number of prey required by early anchovy larvae is not great but a high concentration is required; hence, the patch size could be quite small. It would be of interest in this regard to determine the size, density, and distribution of food patches in the natural environment on a scale appropriate to fish larvae. It would also be of interest to determine the

extent larvae are adapted in their searching behavior to a patchy food distribution.

SUMMARY

1. During the first 2 days of larval life (age 0-1 day) anchovy larvae spent 95% of the time resting. Rest was interrupted once a minute by a burst of continuous swimming lasting 1-2 sec. By age 4 days, yolk was completely absorbed; 85% of the time was spent in intermittent swimming, 7% in feeding, and only 4% in rest. The proportion of time spent in each of these activities remained about the same thereafter.

2. Intermittent swimming was associated with food search. It consisted of repeated sequences of a single tail beat followed by a glide. The speed of the tail was a constant; thus, tail beat frequency was a function of the glide duration. During intermittent swimming tail beat amplitude (A) was the constant proportion of length (L) expressed by the equation, $A = 0.112 + 0.170L$.

3. In continuous swimming, larvae executed a burst of swimming in which no pauses existed between tail beats. Both tail beat frequency and amplitude were modulated during the burst because the larvae accelerated and decelerated. Larvae had a burst speed capability in excess of $25L/\text{sec}$ for bursts lasting 0.1-0.2 sec, but the typical or average burst speed was near $15L/\text{sec}$. The speed (V), tail beat frequency (F), and amplitude (A) relationship for continuous and intermittent swimming were expressed by the equation, $V/A = -1.11 + 1.59F$.

4. The daily rate of movement of larvae excluding rest was estimated using visual and photographic techniques. Measurements taken from cine photographs gave the relationship $V = -0.215 + 1.038L$. Visual observations indicated that average tail beat frequency during intermittent swimming was a constant for larvae of different sizes, and this value was used to provide an additional estimate of the daily rate of movement.

5. The size of the reactive perceptive field for larval anchovy was determined from cine photographs taken in vertical and horizontal planes by plotting the position of prey when larvae first

reacted to them. The limits of the perceptive field were set to include 95% of the prey sighted. The field was elliptical, and increased with length and had a cross section proportional to $0.45L^2$.

6. Larvae first reacted to prey by turning the head toward the prey. The larvae then swam toward it, stopped swimming, coiled the body into an S-shape, and struck at the prey by thrusting the tail backward and extending the head. The total feeding sequence lasted only 1-2 sec. Throughout the sequence the larva adjusted its body to compensate for movements by the prey and slowly moved toward the prey by vibrating the finfold or caudal fin.

7. Only 40% of all feeding sequences were completed. Sequences were ended at all stages up to just before the strike began. The principal cause of failure to complete a feeding sequence after a larva began to form the S-shaped posture was the inability of the larva to close the distance between it and the prey.

8. Under conditions of high food density, larvae fed throughout the day. The average feeding rate for larvae 4 to 27 days old was 1.28 completed feeding sequences/min. During the initial filling of the gut in the morning the mean rate was to 1.75/min.

9. Feeding success of larvae fed *Brachionus* increased rapidly from 11% success on the first day of feeding (age 3 days) to 50% by age 8 days, but the rate of improvement was more gradual thereafter. The relationship between feeding success and age was expressed by the equation, % success = $93.2 (\log \text{age}) - 33.30$. Seventeen-day-old larvae were less successful in capturing *Artemia* for the first time than they had been in capturing *Brachionus*, but after 3 days of feeding experience on *Artemia* the larvae regained their former level of success.

10. The liters of water searched per hour by larval anchovy were estimated by combining the estimate of the reactive perceptive field with an estimate of sustained swimming activity. When the average of the two swimming activity estimates was used, the estimate of volume searched was nearly the same as the relationship, liters searched/hr = L^3 where L is larval length in cm.

11. The density of rotifers and dinoflagellates required for larvae to meet metabolic needs was

calculated from caloric and respiration data, and estimates of volume searched and feeding success. These calculations indicated that anchovy larvae just after yolk absorption require up to 37 times the food density as older larvae. Thus, just after yolk absorption anchovy larvae are more vulnerable to death from starvation than at any other time during the larval stage.

ACKNOWLEDGMENTS

David Holts assisted in all but the work on feeding success which Gary Thomas assisted. Alan Good wrote the program used to analyze the swimming behavior of larvae and the one used to analyze observational data collected on paper tape. James Zweifel fit various models to the swimming data.

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OBSERVATIONS ON SCALE PATTERNS AND GROWTH OF THE PACIFIC SARDINE REARED IN THE LABORATORY

MAKOTO KIMURA AND GARY T. SAKAGAWA¹

ABSTRACT

Scale patterns and growth of Pacific sardine (*Sardinops caerulea*) were studied with laboratory-reared fish held for 24 months. All scales examined after the fourth month had accessory marks. The first accessory mark was formed in August to October and the second accessory mark, in May to August. The accessory marks were indistinguishable from annuli that formed in November to March.

Five possible causal factors of mark formation were investigated—temperature, salinity, gonad index, condition factor, and relative growth rate. Growth rate showed the best correlation. The accessory mark was formed during a period of change in growth rate and the annulus during a period of relatively constant growth rate.

An estimate of the body length-scale radius relation indicated that scales first increase in size at a body length of 33 mm.

Growth in length was rapid from the start of the experiment to the fourth month, after which the increase was gradual. The average instantaneous rate of growth was about 0.47/month during the first 4 months and about 0.03/month thereafter.

It was concluded that the abrupt increase in L_1 that was recorded in the 1940's for the sardine population was probably caused by errors in aging, owing to a change in scale readers and scale-reading criteria. The ages of fish age II and older were probably underestimated by the recent scale readers.

In the course of aging Pacific sardine (*Sardinops caerulea*) from scales, the senior author observed, from comparison of back-calculated lengths with growth curves, that accessory marks or false annuli occurred frequently and were easily mistaken for true annuli. This was contrary to the findings of Walford and Mosher (1943:8-9), who reported that the annulus was "present on all normal scales of an individual" whereas an accessory mark was only rarely present on "all the scales of an individual." Since misidentifying an accessory mark as an annulus can affect the estimated age of a fish, a laboratory experiment was conducted to determine (1) the frequency of occurrence of accessory marks, (2) the time of accessory mark formation, (3) possible factors that may cause accessory mark formation, (4) the time of annulus formation, and (5) the seasonal pattern of sar-

dine growth. The experiment was initiated in May and was terminated approximately 24 months later. Results from the first 12 months of the experiment were reported by Kimura (1970), who showed that an accessory mark was present on scales of 4.5- to 5.0-month-old fish. This report is a more comprehensive presentation of results from the entire experiment.

METHODS

REARING

The collection of sardine eggs and the hatching and rearing of the young in the laboratory for the first 12 months were described by Kimura (1970). The general procedures, including those used after the 12th month, are briefly reviewed as follows. In May 1968, sardine larvae were hatched from eggs collected in plankton tows off San Diego, Calif., and the larvae were held in a

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polyethylene bag, which was suspended in a 4.6-m diameter pool (13.2 kliter). The pool also contained about 15 northern anchovy (*Engraulis mordax*) larvae. A 1,500-w mercury lamp that was suspended about 1 m above the bag provided illumination and a source of heat. The larvae were fed daily with plankton collected in Mission Bay, Calif., and live *Artemia*. On the 29th day the larvae were released into the pool. Feeding continued with plankton and live *Artemia* up to the 45th day, after which frozen *Artemia* and dry trout food were substituted. The daily ration was about 10% of the estimated total weight of fish alive on a given day, based on the average weight of fish sampled in the previous month.

On the 31st day the density of sardine larvae was noticeably reduced. Since few dead larvae were found during the previous days, the anchovies (average length 66 mm) were suspected of feeding on the sardines (average length 24 mm). Analysis of stomach contents of three anchovies revealed that they were indeed feeding on the sardines.²

During the first few months of the experiment, water was added to the pool only periodically to remove surface scum. But beginning on the 61st day, seawater was circulated continuously through the pool at an initial rate of about 19 liter/min. This rate was increased on the 180th day to about 34 liter/min.

SAMPLING

Fish were sampled and sacrificed at various intervals during most of the duration of the experiment. About 7-17 larvae were sampled daily from the polyethylene bag during the first month. During the second month 6-26 larvae were sampled primarily on a weekly basis. Starting with

the third month and continuing through the 12th month, about 20-24 fish/month were sampled. After the 12th month, the sampling rate was reduced to 11-14 fish/month until an unusually large mortality from unknown causes reduced the population to 12 fish in the 16th month. Two more samples were taken thereafter; in one sample four fish were measured for length and returned to the pool. After the 24th month, the seven surviving fish were sampled and the experiment was terminated.

Standard length, total weight, gonad weight, and six scales removed from the body area at the tip of the pectoral fin (see Walford and Mosher, 1943:4) were obtained from most samples.

Water temperature was recorded daily on a thermograph. The monthly mean temperature ranged from 15.3° to 25.0°C and was generally 2.9°C higher than the monthly mean surface temperature recorded off the Scripps pier, La Jolla (Kimura, 1970), site of the water intake for the experimental pool³ (see Lasker and Vlymen, 1969).

Salinity measurements were made by daily titrations from surface water sampled off Scripps pier. The mean values ranged from 33.09 to 34.38‰. It was assumed that water salinity was the same off the Scripps pier and in the experimental pool.

SCALE MEASUREMENTS

Scales were placed between two glass slides and viewed on a scale projector that magnified them 30 times. All marks that appeared to be annuli were recorded and the widths from focus to mark and focus to margin in the anterior field were measured.

ANALYSIS

Gonad weight was expressed as a percentage of total weight. This was designated a gonad index, or relative measure of sexual development.

The relative "fatness" of a fish was estimated

² To our knowledge there have not been previous reports on predation of sardine larvae by anchovies. The significance of our observation is that predation by anchovies may have contributed to the decline of the Pacific sardine population. Our anchovies were hatched from eggs and were 44 days older than the sardines. This difference in age (size) between the species is also found in the wild; the northern anchovy has a peak spawning period during January-March and the sardine, during April-June (Ahlstrom, 1966). The young of both species coexist in the California Current; thus it is conceivable that predation by anchovies is an important source of sardine natural mortality.

³ The experimental pool was located at the Southwest Fisheries Center, about 1 km from the Scripps pier.

TABLE 1.—Results of aging of 205 known age, laboratory-reared sardines from scales.

Age (months)	Total number of fish	Total number of marks	Actual		Estimated				Percent disagree- ment
			Number with:		Number with:				
			0 mark	1 mark	0 mark	1 mark	2 marks	3 marks	
5	20	1	20	0	20	0	0	0	0
6	20	1	20	0	20	0	0	0	0
10	15	2	0	15	0	12	3	0	20.0
11	21	2	0	21	0	10	11	0	52.4
12	24	2	0	24	0	18	6	0	25.0
13	11	3	0	11	0	3	8	0	72.7
14	12	3	0	12	0	2	6	4	83.3
15	14	3	0	14	0	0	12	2	100.0
16	64	3	0	64	0	4	50	10	93.7
18	4	3	0	4	0	0	3	1	100.0

TABLE 2.—Frequency and percent (in parentheses) of Pacific sardines with various number of scale marks, as determined from scale reading. (Sardines were reared in the laboratory for 24 months.)

Age (months)	Number of fish	No mark	Accessory mark I	Annulus I	Accessory mark II	Annulus II
1	3	3 (100)				
2	8	8 (100)				
3	17	17 (100)				
4	9	4 (44)	5 (56)			
5	20		20 (100)			
6	20		20 (100)			
7	20		20 (100)	10 (50)		
8	20		20 (100)	13 (65)		
9	20		20 (100)	18 (90)		
10	20		20 (100)	20 (100)		
11	21		21 (100)	21 (100)		
12	24		24 (100)	24 (100)		
13	11		11 (100)	11 (100)	4 (40)	
14	12		12 (100)	12 (100)	6 (60)	
15	14		14 (100)	14 (100)	10 (100)	
16	64		64 (100)	64 (100)	64 (100)	
18	4		4 (100)	4 (100)	4 (100)	
24	7		7 (100)	7 (100)	7 (100)	7 (100)

by a condition factor (MacGregor, 1959). The factor (K) is calculated as a ratio of the weight in grams (W) to the cubic power of length in millimeters (L): $K = (W/L^3) \times 10^7$.

Back-calculated lengths from scale measurements were derived by two methods. Method one was by direct proportion, $L_m = (s_m/s_r)L$, where L_m = back-calculated length at time of mark (m) formation, s_m = scale width from focus to mark m , s_r = scale width from focus to margin, and L = length at sampling. Method two was also by direct proportion but with a correction factor (c) for body length when scales first increase in size in the Pacific sardine. The method uses the equation $L_m = c + (s_m/s_r)(L - c)$.

ACCESSORY MARKS AND ANNULI

FREQUENCY OF OCCURRENCE

An annulus is generally believed to form at annual intervals, usually as the result of a slowing down in growth such as occurs in winter for temperate species. An accessory mark, on the other hand, is believed to occur, if at all, at irregular intervals (Walford and Moser, 1943), the causes of which are unknown.

We examined the scales of the laboratory-reared fish and were unable to distinguish between the two types of marks. To test if other scale readers similarly could not distinguish accessory marks from annuli as we did, a series of scales from the laboratory-reared fish was mixed

with scales collected from wild fish and three experienced scale readers read the scales (Table 1). The percent error was as large as 100%, which indicates that accessory marks can indeed be easily misidentified as annuli.

TIME OF FORMATION

As many as four marks were observed on some scales. The percentage of fish with various numbers of marks was tabulated for each sample (Table 2). The results show that the first mark was formed from August to October (4-5 months old), the second from November to March (6-10

months old), the third from May to August (13-15 months old), and the fourth sometime after November (18 months old) but probably before January (20 months old). This January date for the fourth mark was deduced from two scales collected in late December from the bottom of the pool, but the data are not given in Table 2. The two scales had four distinct marks, but it is not known whether the scales were from one or two fish. The bottom of the pool was cleaned daily.

Based on the above criteria of an annulus and accessory mark, the second and fourth marks are annuli, and the first and third marks are accessory marks. The interval between annuli was about 12 months, and that between accessory marks was only 9 months.

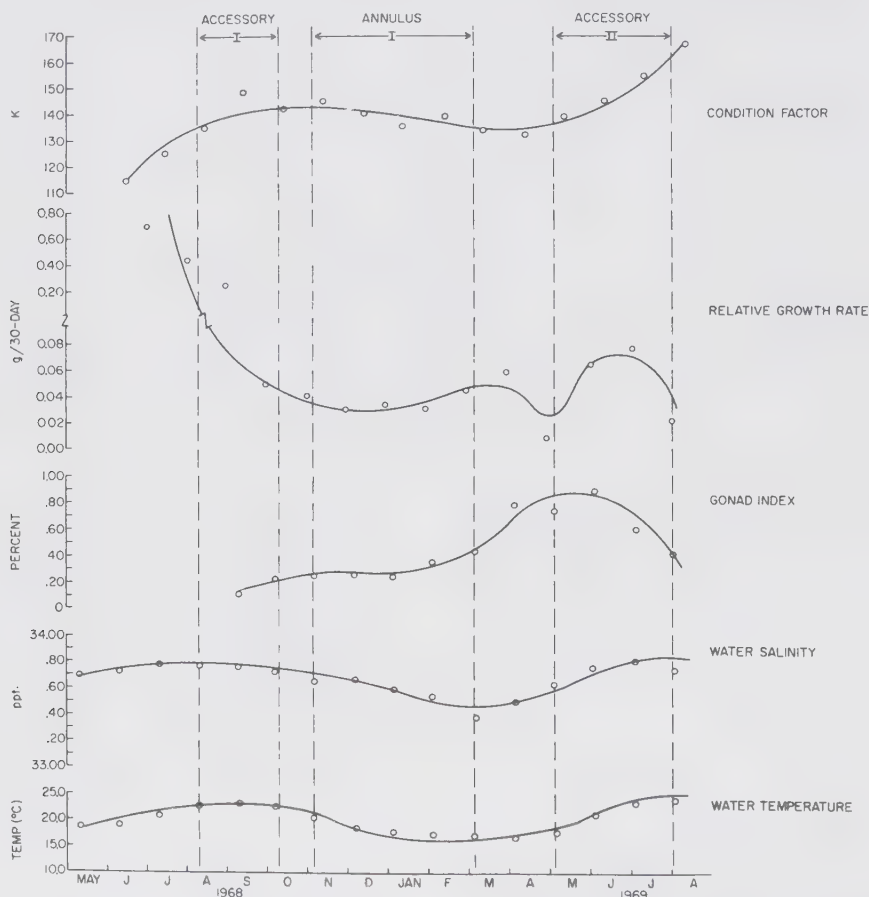


FIGURE 1.—Four possible factors that may be associated with mark formation on scales of Pacific sardines. Periods of mark formation are delineated by vertical lines.

POSSIBLE FACTORS AFFECTING MARK FORMATION

Water temperature and salinity, gonad index, condition factor, and growth rate were analyzed to determine whether they affected mark formation (Figure 1). Growth rate appeared to be best correlated with mark formation.

Kimura (1970) used monthly growth increments⁴ for the first year to show that formation of the accessory mark was associated with maximum growth, and formation of the annulus was associated with the onset of rapid growth. His choice of growth increments for his analysis was not ideal because the magnitude of an increment is dependent on the size of the fish. We therefore chose to use the instantaneous rate of growth, $g = (\ln L_t - \ln L_0) / (t - t_0)$, Ricker (1958) on a 30-day basis to analyze the data from the entire experiment. The results (Figure 1) show that the accessory marks formed during periods of change in growth rate, whereas the annulus formed during a period of relatively constant growth rate.

GROWTH

BODY LENGTH-SCALE RADIUS RELATION

A body length-scale radius relation was fitted by least squares to data from 283 fish. A straight line of the form $Y = 32.856 + 9.030X$, where Y = standard length and X = scale radius, was calculated (Figure 2). The intercept of the line, or 32.856, is an estimated body length when scales first increase in size in the Pacific sardine. This estimate is probably too high, because scales with several circuli were observed on 26- to 30-mm long fish.

Landa (1953) reported 12 positive intercept values (68-191 mm) and 1 negative value (-102 mm) for body length-scale radius relations of fish caught by the commercial fishery in the 1940's. Compared to our estimate, his es-

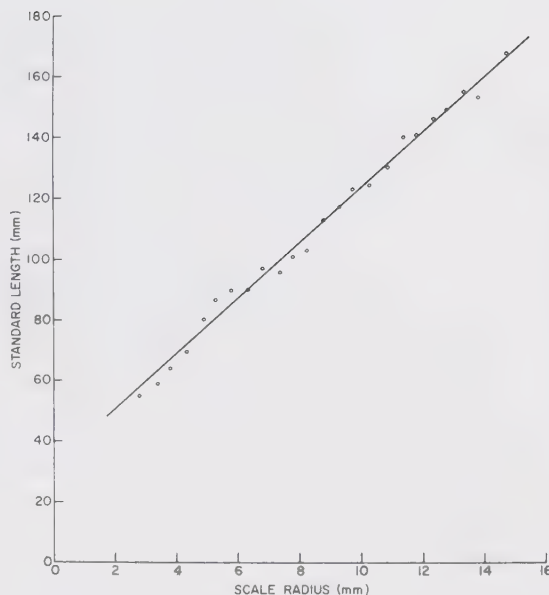


FIGURE 2.—Body length-scale radius relation for 283 laboratory-reared Pacific sardines.

timates are considerably larger. One reason for the difference is Landa used data from large fish (mean lengths of 186-228 mm), whereas we used data from small fish (mean length of 115 mm). This suggests that a relation over the entire size range of sardines may be nonlinear, although it is linear over a short segment of the curve. The parameters of a linear relation could hence vary, depending on the segment of the curve being examined.

WEIGHT-LENGTH RELATION

Data from 326 fish were used to estimate the weight-length relation. The relation (Figure 3) appears to underestimate the average weight of fish greater than 135 mm long. This is probably because the weight-length relation was based on data from individual fish whereas the data points in Figure 3 represent average weights for 5-mm groupings of lengths.

Clark (1928) estimated a weight-length relation for sardines landed at San Pedro, Calif., in the 1920's. Her estimate was compared to ours

⁴ In Kimura's Figure 3 the notations for weight and length increments are mislabeled. The increments are not percentages but absolute values.

SEASONAL GROWTH PATTERN

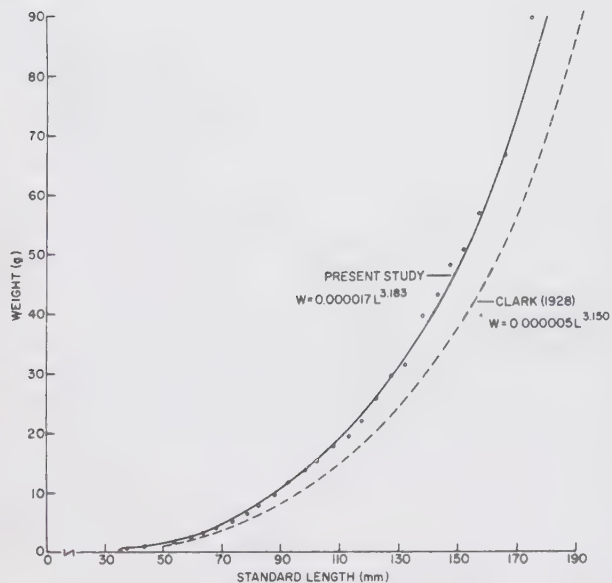


FIGURE 3.—Weight-length relation for the Pacific sardine.

(Figure 3) and found to be significantly different based on analysis of covariance ($F = 18.02$, $df = 1, 237$). The laboratory-reared fish were appreciably heavier for a given length than sardines caught in the 1920's. This may be attributed to several causes, among them difference in diet, in amount of exercise, and in the range of sizes sampled.

Growth of the Pacific sardine has been well documented by several investigators (e.g., Walford and Mosher, 1943; Phillips, 1948; Felin, 1954; Clark and Marr, 1955). Most of the studies have concentrated on estimating growth based on scale readings of fish caught by the commercial fishery.

Another method of estimating growth is by rearing experiments. Although we recognize the limitation of laboratory vs. natural conditions, we believe that estimates of growth of laboratory-reared sardines can indicate the general trend in growth in the wild. We therefore estimated growth of our laboratory-reared sardines.

As shown in Figure 4, growth in length was rapid from the start of the experiment to the fourth month, after which the increase was more gradual. The average instantaneous rate of growth was about 0.47/month during the first 4 months and about 0.03/month during the fifth to 24th month. In contrast, growth in weight increased somewhat exponentially during two phases: during the first 4 months and again during the fifth to 14th month (Figure 5).

Walford and Mosher (1943) reported the standard lengths of juvenile sardines caught in monthly samples in the late 1930's. Although the date of birth, and hence the exact age, of

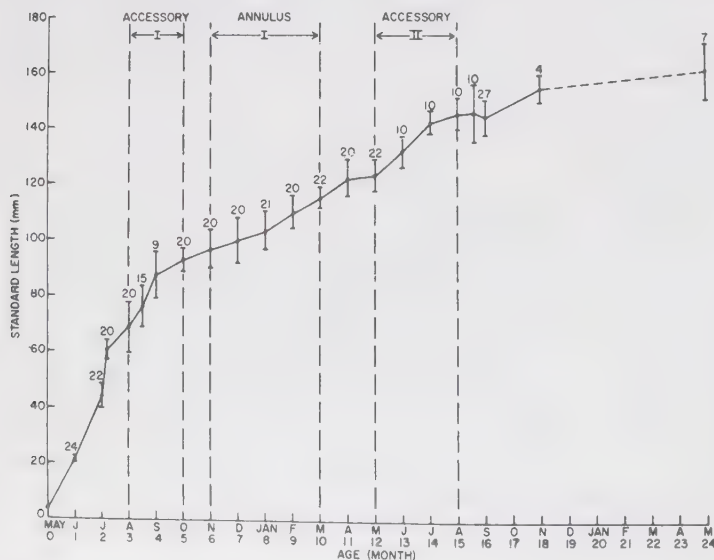


FIGURE 4.—Growth in length of Pacific sardines reared in the laboratory for 24 months. Mean length is represented by a circle, and one standard deviation is shown on each side of the mean. The sample size is also indicated. The first accessory mark occurred in August-October, and the second in May-August. The first annulus formed in November-March, and the second apparently in December.

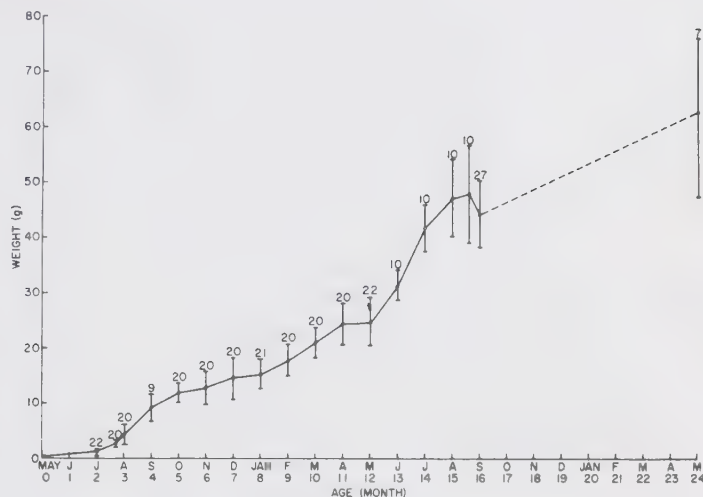


FIGURE 5.—Growth in weight of Pacific sardines reared in the laboratory for 24 months. Mean weight is represented by a circle, and one standard deviation is shown on each side of the mean. The sample size is also indicated.

their fish was not known, we compared their data for the 1937 and 1938 year classes with ours (Figure 6). The results indicate that although growth of the 1937 year class was fast, growth was similar in fish caught in the 1930's and in the laboratory-reared fish.

Marr (1960) presented data on the average length at time of first annulus formation (L_1) and showed that there was a sharp change in L_1 to a higher level with the 1944 year class landed at San Pedro. Using his data, we calculated separate estimates of average L_1 : one for the 1934-43 year classes, and another for the 1944-57 year classes. The estimates are 101.3 and 131.5 mm, respectively. Compared with our estimate of 103.0 mm, growth of the 1934-43 year classes was almost identical to that for the laboratory fish, and growth for the 1944-57 year classes appears to have been faster than that for the laboratory fish. This faster growth may be an artifact and is discussed in a later section.

BACK-CALCULATED LENGTHS

Back-calculated lengths were computed for two samples, taken in September (16th month) and May (24th month). We reasoned that the back-calculated lengths would give an independ-

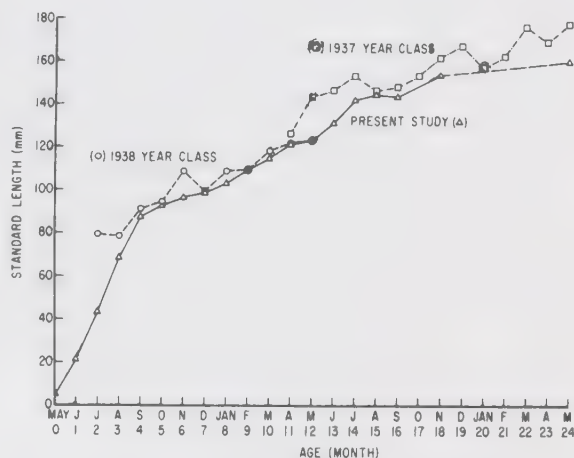


FIGURE 6.—Comparison of growth of juvenile sardines caught in the 1930's with growth of laboratory-reared sardines. Data for the 1937 and 1938 year classes are from Walford and Mosher (1943).

ent estimate of the time of mark formation, if growth is assumed to follow that shown in Figure 4. The average back-calculated lengths based on two methods are shown in Table 3. The first method gave lower estimates than the second. Both methods, however, gave back-calculated lengths that were reasonably similar to average lengths of samples collected during the period when the marks formed.

TABLE 3.—Back-calculated length of sardines sampled on two dates. The two methods of back-calculating length are discussed in detail in the text; in general, method 1 is by direct proportion, and method 2 is by direct proportion with a correction factor for the body length-scale radius relation.

Sampling date	Method	Average length (mm) at:					Sample size
		Accessory mark I	Annulus I	Accessory Mark II	Annulus II	Margin	
September	1	71.5	99.9	135.6	--	143.3	27
	2	88.9	110.6	137.8	--	143.3	27
May	1	75.1	104.7	137.4	153.1	160.3	7
	2	93.6	116.8	142.3	155.0	160.3	7

DISCUSSION

MARK FORMATION ON SCALES

Walford and Mosher (1943) indicated that on sardine scales an accessory mark was distinguishable from an annulus by its finer sculpturing and its rare occurrence on all scales of an individual. The results of our study on sardines reared in the laboratory showed that accessory marks occurred on all scales examined after the fourth month, and they were generally indistinguishable from annuli. But for some scales in which the accessory mark was distinguishable from an annulus, the identifiable characteristic was the fine sculpturing mentioned by Walford and Mosher.

Interruptions in the growth pattern are generally assumed to form marks on scales (e.g., see Van Oosten, 1957). It is also widely assumed that the driving mechanism behind mark formation is temperature, through the influence of a fish's metabolism (Brown, 1957). Our results indicate that mark formation is unrelated to temperature, but appears to be related to growth rate. Hogman (1968) obtained somewhat similar results in his experiments with coregonids. He found that formation of marks was closely related to growth and somewhat related to temperature. However, Hogman indicated that light period may be the primary driving mechanism. Bilton and Robins (1971) found that mark formation was correlated with increase in food supply, but not with resumption of feeding after starvation in sockeye salmon. Their experiments with light period proved inconclusive. It thus appears that mark formation in fishes is probably related to growth, al-

though the actual driving mechanism(s) have so far not been clearly identified.

ERROR IN AGING

Scales are routinely used to age and study growth of the Pacific sardine. Our results indicate that extreme caution must be exercised in aging because of the presence of accessory marks on scales. Furthermore, since the annulus is formed during the winter, the actual age of a fish at time of first annulus formation may vary depending on its date of hatching. In our study the first annulus was laid down after the sixth month for fish hatched in May. May is the middle of the heavy spawning season for the Pacific sardine, but the season extends from March to October (Kramer and Smith, 1971).

Kimura (1970)⁵ conducted an experiment to test the consistency of early and recent scale readers in aging sardines from scales. He found that the abrupt increase in L_1 , as reportedly observed in the 1940's by Marr (1960) for sardines landed at San Pedro, may have actually been caused by a change in scale readers and in criteria used in reading scales. We compared our average length at annulus formation with the average L_1 of fish aged by the early ($L_1 = 101.3$ mm) and recent ($L_1 = 131.5$ mm) scale readers, and discovered that the early readers probably aged sardines correctly, whereas the recent readers probably underestimated the age of age II

⁵ Kimura, M. 1970. Possible errors in locating the first scale annulus and in estimating the length of Pacific sardines. Manuscript filed at National Marine Fisheries Service, Southwest Fisheries Center, La Jolla, CA 92037.

and older fish. If this was the case, and assuming that growth has not appreciably changed, then the number of fish that was incorrectly aged as age I by recent scale readers was at most equal to the number of fish correctly aged as age I. This is deduced from the fact that the presumably overestimated L_1 of 131.5 mm is about midway between our L_1 of 103 mm and L_2 (=length at time of second annulus formation) of about 160 mm.

Back-calculated lengths for Pacific sardines (Marr, 1960) have been based on Method 1. A statistical test of the intercept of our body length-scale radius relation (Figure 2) indicated that the intercept is not significantly different from zero ($t = 1.831$, $df = 282$). Although this indicates that Method 1 is acceptable, the back-calculated lengths at first annulus are appreciably and significantly different between Method 1 and Method 2 (Table 3). It is therefore advisable that Method 2 be used since it is the better procedure (Ricker, 1969).

We conclude from these results that a bias may be present in published accounts of the age composition of the Pacific sardine catch, which in turn may have affected studies on the population dynamics of the Pacific sardine. We recommend that the method of aging Pacific sardines be re-evaluated, perhaps with the consideration of modifying the scale method so that the scale reader is made aware of the length of fish being aged or even utilizing other hard parts for aging, and that appropriate steps be taken to eliminate aging errors in the historic records on age composition of the catch. We realize that this task will not be easy, but it may be worthwhile because of the frequent use of the records to analyze fisheries hypotheses.

ACKNOWLEDGMENTS

We thank C. E. Blunt, Jr., J. E. Hardwick, and J. S. MacGregor for participating in our test to determine whether accessory marks can be misidentified as annuli. P. Paloma and A. Saraspe assisted in hatching and rearing the sardines. D. Kramer, W. H. Lenarz, J. S. MacGregor, and A. M. Vrooman kindly reviewed the

manuscript and gave helpful suggestions. J. R. Thrailkill drew the figures. We are indebted to these individuals.

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SEASONAL AND GEOGRAPHIC CHARACTERISTICS OF FISHERY RESOURCES

California Current Region--VIII. Zooplankton

David Kramer and Paul E. Smith

Plankton is defined in most dictionaries simply as the passively floating or weakly swimming animal and plant life of a body of water (zooplankton and phytoplankton, respectively). Such an uninteresting definition in no way acknowledges the important roles of such organisms in the food chains in bodies of water and their tremendous variety in species and morphology.

In the California Current region alone, it has been estimated that, for zooplankton only, there are at least 546 invertebrate species (Isaacs, Fleminger and Miller, 1971) and approximately 1,000 vertebrate species, that is, as fish larvae. Such larvae and, in some instances, their eggs were the bases of the first seven reports in this series (Kramer and Smith, 1970a, b, c, d, 1971a, b, c). The variety of species in this region, just for a part off central Baja California, was shown by Ahlstrom and Thraill (1963, Table 5). They listed about 145 invertebrates and 36 vertebrates in only 12 plankton samples. Another example of variety of species found near our survey pattern was reported by McGowan and Fraundorf (1966, Table 7) for a small area southeast of Cabo San Lucas near the northern limits of the zooplankton fauna of the equatorial water mass. This report on zooplankton diversity listed 69 species of invertebrates and 81 species of fish larvae collected in 24 plankton samples.

Zooplankton's Essential Role

Zooplankton is not reported here as a fishery, but in recognition of the essential part its vast community plays in relation to the fish resources. In worldwide fisheries, its supply forms the entire diets of plankton feeders such as anchovies, herrings, pilchards, and menhaden. Certain of its constituents, possibly including some phyto-

plankton, are essential foods for most stages of larval fish development. One of the greatest phenomena of marine-animal development is that of the growth of baleen whales, which feed exclusively on plankton, sometimes only on the shrimplike plankter "krill", a large euphausiid. One example in particular is the blue whale's growth. At birth, this whale is about 7 m long and 2,000 kg in weight (21-23 ft, 2+ tons). Seven months after birth, it is about 16 m long and weighs 23,000 kg (48-52 ft, 25 tons)--feeding only on krill! (Rice, 1972.)

This report deals with the seasonal and geographic characteristics and variations of zooplankton biomass in the California Current region. Organizations, area of investigation, and treatment of data were presented in the first report of this series (Kramer and Smith, 1970a). In addition, we will discuss the annual cycles (variation) for different parts of the survey area north to south and inshore-offshore.

Data Processing

Our previous descriptions of processing data did not include discussion of the methods used to collect and process plankton. Detailed descriptions of the methods for collecting and processing data in the California Current region were described by Kramer, et al. (in press) and in some detail by Smith (1971).

For the data 1951-60, the following methods were used to collect plankton. Each sample was taken with the standard CalCOFI net constructed of silk mesh (bolting cloth), mouth diameter 1 m, and mesh size approximately 0.55 mm. Occasionally a nylon net of the same mouth opening and mesh size was used. A flow meter in the mouth of the net

permitted calculation of the amount of water strained. Each tow was made by sinking the net at 50 m per minute to a depth of about 140 m (200 m of wire out, depth permitting) and retrieving it at 20 m per minute while maintaining a wire angle of 45 degrees. The ship's speed during a tow was about 2 knots.

Each sample was preserved in 5% formalin and buffered with sodium borate. The samples were brought back to the laboratory and measured by the displacement method described by Ahlstrom and Thraillkill (1963), or by a method developed by Thraillkill, described by Kramer, et al. (in press). Both methods are accurate to ± 1 ml. Smith (1971) discussed the variations due to shrinkage and interstitial liquid as previously reported by Ahlstrom and Thraillkill (1963). Two volumes, reported as ml/1,000 m³ water strained, were determined for each sample: first, the total volume and, second, the total volume less large organisms--5 ml or greater--usually jellies or jellylike organisms. (Juvenile and small adult fishes captured by the net are not considered planktonic.) Each sample was then sorted for all fish eggs and larvae. The sorted sample was studied further for selected invertebrates (e.g., Isaacs, et al., 1969, 1971). Also see their Table 1 in each volume, which cites investigators, their publications, and interests.

Our treatment of the data is for zooplankton only in terms of total volumes of all organisms with no separation by constituents or groups. Isaacs, et al. (1969) reported on the seasonal and annual variability among 17 functional groups of zooplankton for the spring (April cruises) and fall (October cruises) for 1955 through 1959. In 1971, they reported on winter variability for January in 1955 through 1959.

Seasonal and Geographic Distribution

The variations in seasonal and geographic distributions for 1951-60, shown in Figures 1 and 2, are similar even though the diagrams are from two sets of data and are presented in somewhat different ways. Figure 1 shows summaries of plankton volumes only for organisms less than 5 ml, expressed as medians of volumes per 1,000 m³ of water strained--the medians represent the central values of suites of samples. Figure 2 summarizes plankton volumes only for organisms greater than 5 ml, expressed as percentages of occurrences in plankton hauls. Smith (1971,

Figure 2) presented the same data in a figure of relative abundances in an atlas of plankton volumes for every survey conducted by the CalCOFI from 1951 through 1960. The basic data for all surveys, 1951 through 1966, were reported by the Staff, South Pacific Fisheries Investigations (1952, 1953, 1954, 1955, 1956) and Thraillkill (1957, 1959, 1961, 1963, 1969, MS).

Each figure indicates the trends to be expected during a year's production of plankton, wherein peaks of abundance occur from spring to summer and decreases occur in fall and winter. (Data were insufficient for summaries to be made for August, September, and November.)

Temperature and Zooplankton

Temperatures at 10 m, summarized for the 10 years in the same pooled areas (Figure 3)--see Kramer and Smith, 1970a, Figure 2--indicate the trends of centers of greatest plankton abundance within a particular range of low temperatures, 12°-15° C. (The 10-m depth is regarded as mid-depth or average of stratum between surface and thermocline. Ten-meter temperatures have been published in atlases for 1949 through 1969 for all CalCOFI surveys (Anonymous, 1963; Wyllie and Lynn, 1971).)

Zooplankton production in "warm" and "cold" years bear out the trends to be expected from the data depicted in Figures 1, 2, and 3. Reid (1962, Figure 5) showed that for each year, 1949 through 1960, plankton volumes were high with low temperatures and low with high temperatures. He also depicted two figures from Thraillkill (1959, 1961) showing averages of high volumes in 1956, a cold year, and low volumes in 1958, a warm year. Ahlstrom and Thraillkill (1963) cited the warm year 1959 and the fact that plankton volumes then were the lowest in a decade.

Annual Cycles

Another illustration of seasonal and geographic changes is in the summarization of data to show annual cycles by region and pooled area (Figure 4). Here, monthly median volumes are presented for six regions, north to south, at 40-mile intervals onshore-offshore. Each curve is an annual cycle beginning in each January (J), summarized over the 10 years, 1951-60. Each

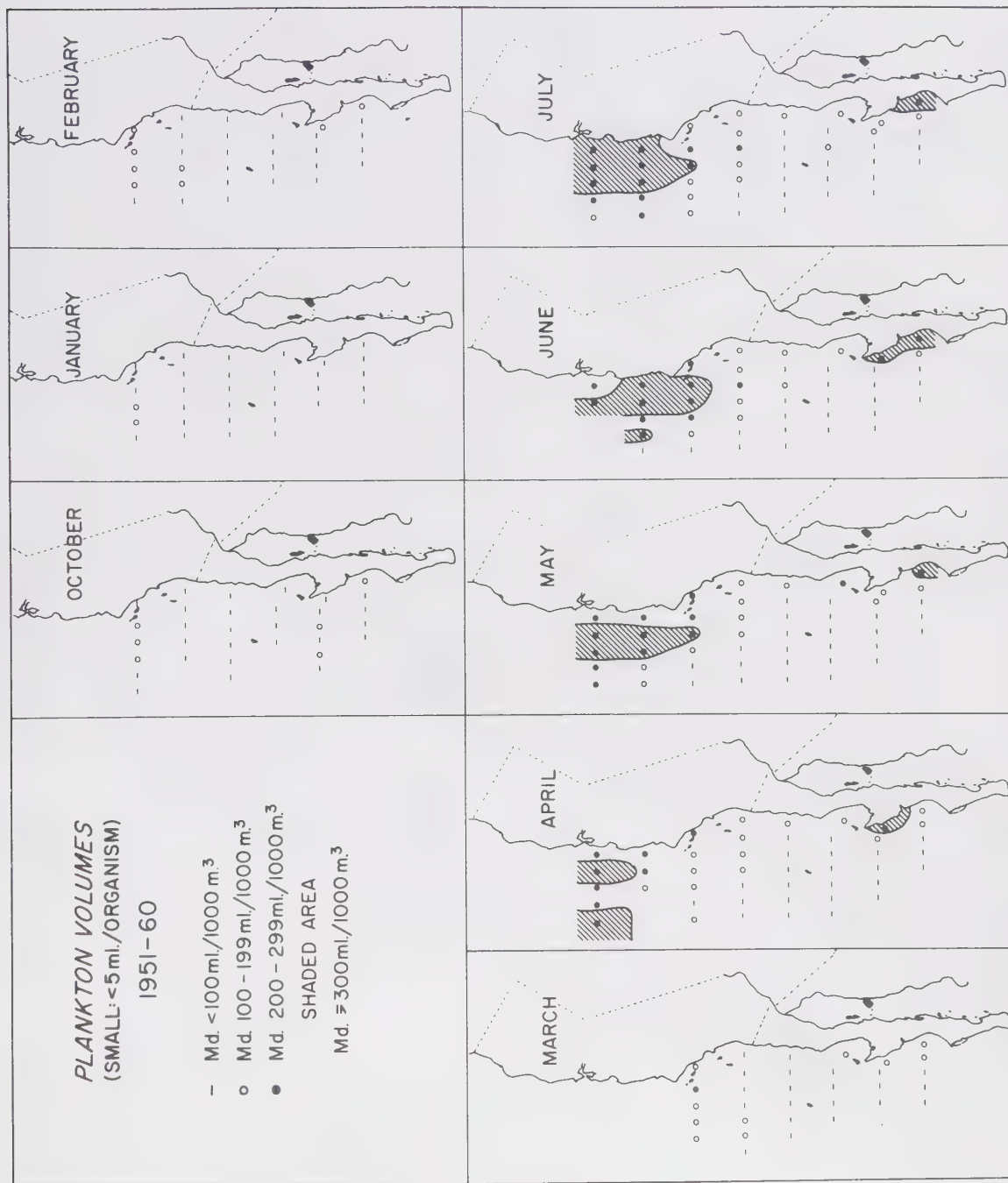


Fig. 1 - Medians of plankton volumes consisting of organisms less than 5 ml collected on survey pattern of California Cooperative Oceanic Fisheries Investigations (CalCOFI), 1951-60. Each circle, line, or dot represents a pooled statistical area (see Kramer and Smith, 1970a).

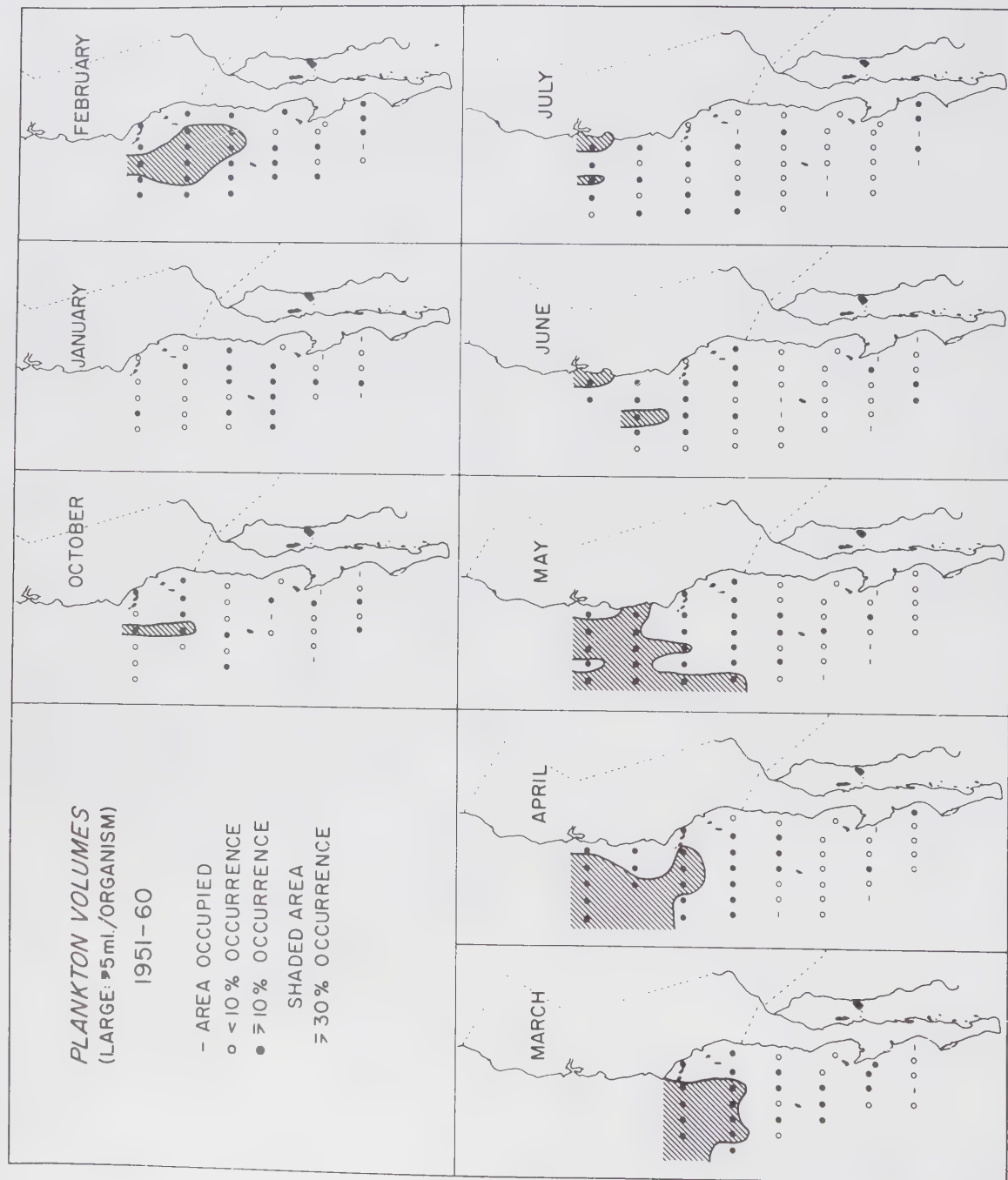


Fig. 2 - Percent occurrence of plankton volumes, consisting of organisms equal to or greater than 5 ml, collected on survey pattern of California Cooperative Oceanic Fisheries Investigations (CalCOFI), 1951-60. Each circle, line, or dot represents a pooled statistical area (see Kramer and Smith, 1950a).

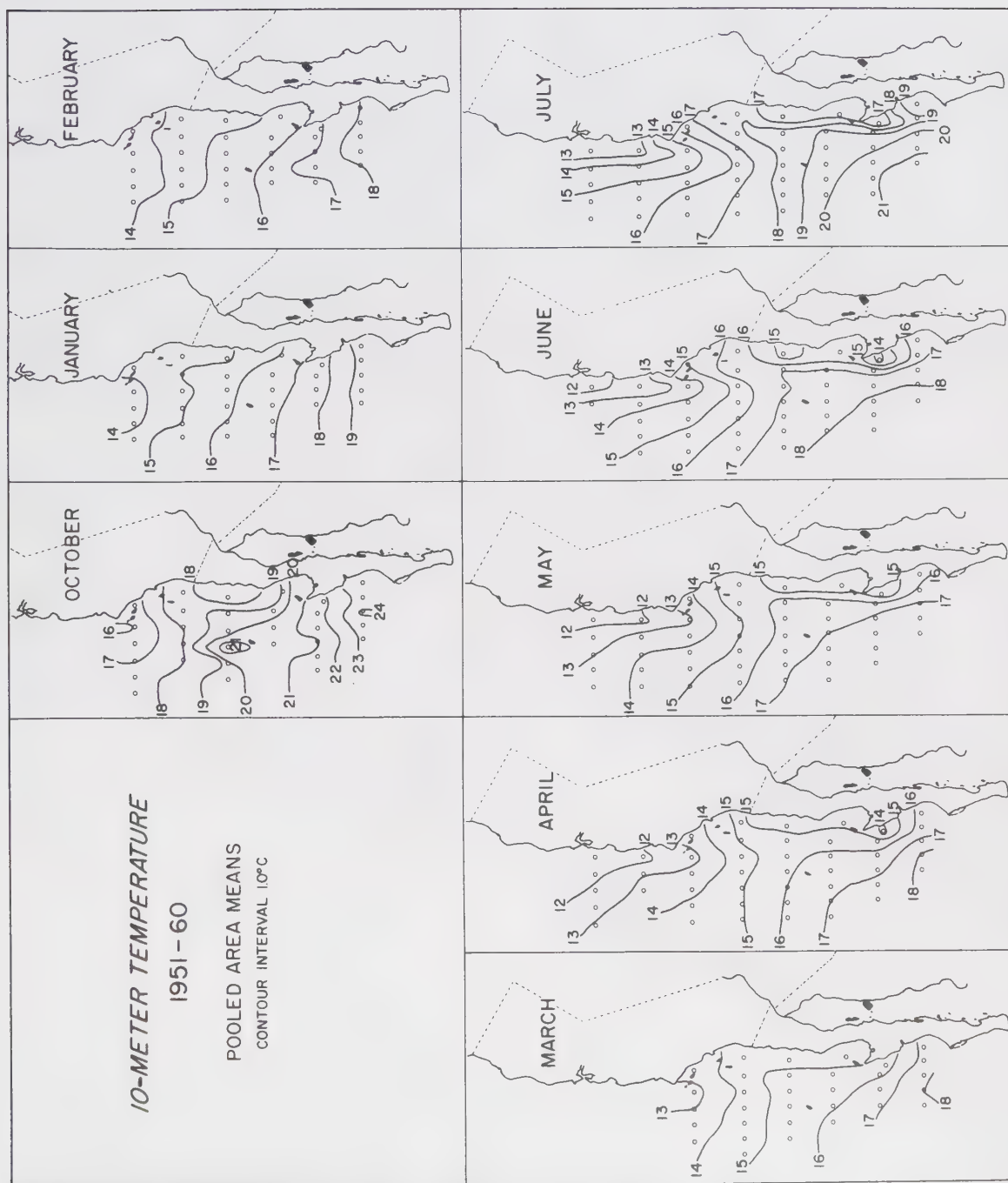


Fig. 3 - Pooled area means of 10-m temperatures in survey pattern of California Cooperative Oceanic Fisheries Investigations (CalCOFI), 1951-60. Each circle, line, or dot represents a pooled statistical area (see Kramer and Smith, 1970a).

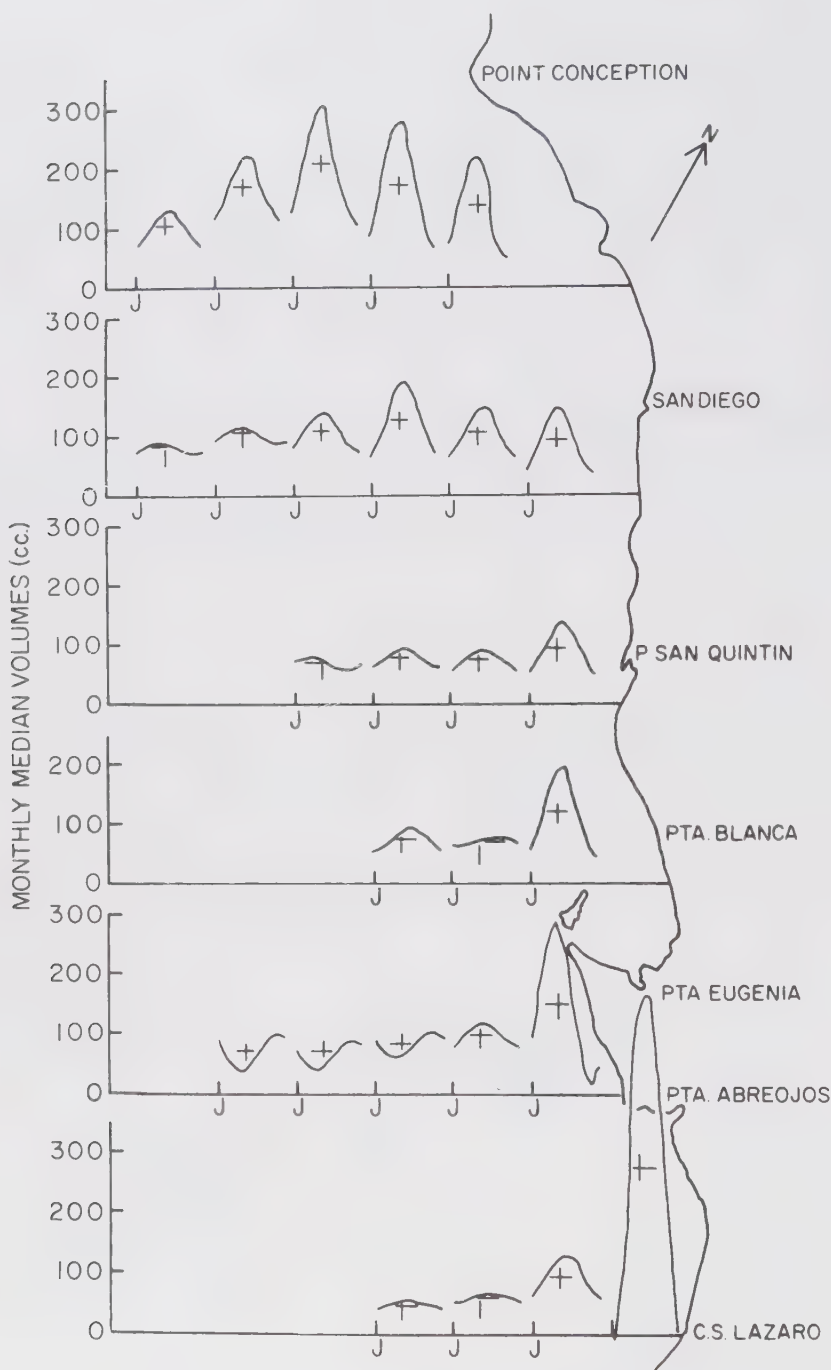


Fig. 4 - Annual cycles of plankton volumes (monthly medians) collected in survey area of California Cooperative Oceanic Fisheries Investigations (CalCOFI), 1951-60. (See text.) There are no curves shown for offshore areas, Punta San Quintin, and south because there were no significant annual cycles in monthly median volumes in those regions.

vertical line in each curve represents June and each horizontal line is the annual average. Here, as in Figures 1 and 2, high abundance occurs in mid-year when day length is longest and temperatures are low, as shown in Figure 3.

Determinants of Zooplankton Concentrations

Zooplankton concentrations are established by the rates of production of their components, their growth rates, their natural mortality, and predation on their populations. Very little is known about any of these since our data are based only on that proportion retained by our rather coarse-mesh net. A large part of the plankton escapes through this net--those immature stages that are smaller than our primary targets, fish eggs and larvae. It is highly probable that a very large part of the escaping plankton is the food in sizes needed by the fish larvae we

collect--for example, as listed for anchovy larvae by Kramer and Zweifel (1970, Table 2).

It has been hypothesized that high plankton concentrations are the result of (1) high nutrient content, and (2) transport of plankton during certain seasons. Reid, Roden and Wyllie (1958) observed that dense plankton in summer months and high phosphate-phosphorous (PO_4 -P) content coincide with low temperatures in the California Current region. Reid reported in 1962 that dense zooplankton might be the result of its transport into the region by the west wind drift from dense subarctic populations. Our major problem in this study is that estimates and predictions of rates of water movement, and life histories of plankton that are not well known, are inadequate to show what parts in their different stages of development drift in and out of, or stay in, the region.

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COLLECTING AND PROCESSING DATA ON FISH EGGS AND LARVAE IN THE CALIFORNIA CURRENT REGION

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ABSTRACT

Descriptions are given for the methods used by the California Cooperative Oceanic Fisheries Investigations to collect and process plankton. These include details of the design of the station pattern in the survey area, the gear and methods used for plankton hauls, measuring plankton, and sorting plankton for fish eggs and larvae; some procedures for identifying fish eggs and larvae; details of "hand" processing data for standardization of numbers of organisms collected in all plankton hauls; calibration of flowmeters; and some new procedures for automatic data processing.

INTRODUCTION

For more than 20 years the California Cooperative Oceanic Fisheries Investigations (CalCOFI) have conducted a program of intensive research in the California Current region in a designated area of approximately 500,000 square miles from the California-Oregon border to the tip of Baja California. The investigations were originated in 1949 to determine the reason for the decline of the Pacific sardine fishery. Since then, the data have contributed a wealth of information from which it has been possible to study the effects of the biological, physical, and chemical environment on all the resources in the area.

The chief participants in CalCOFI in ships, personnel, equipment, shoreside facilities, and data collection, processing and analyses are the California Department of Fish and Game (CF&G) on the evaluation of resources by census of young and adult fishes, the University of Cal-

ifornia, Scripps Institution of Oceanography (SIO), on the studies of the physical and chemical data and selected groups of invertebrates, and the National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), formerly the Bureau of Commercial Fisheries, on the evaluation of resources by censuses of fish eggs and larvae. Other participating groups are the California Academy of Sciences and the Stanford University, Hopkins Marine Station, chiefly in laboratory research.

It is the purpose of this report to describe the methods and gear used by the CalCOFI for collecting and processing data on fish eggs and larvae. Some of these have been described in varying detail (Ahlstrom, 1948, 1950) but none with the full treatment that we feel is warranted, as now reported here, in view of the requests for greater detail by visitors to our laboratory and some investigators who have cooperated with us in data collection at sea.

THE SURVEY PATTERN AND AREA

The pattern of stations (Fig. 1) covered by most of the CalCOFI surveys was designed originally on the basis of a centric-systematic-area sampling scheme (Milne, 1959) to determine the major spawning areas of the Pacific sardine off the coasts of the United States and Baja California, Mexico. This was done by conducting surveys on lines spaced 120 miles apart from the Columbia River to Sebastian Vizcaino Bay. As the spawning areas were delimited, additional lines of stations were added between the cardinal lines, and the surveys were concentrated off the coasts of California and Baja California.

The original lines of the pattern were based on line 80 off Point Conception, Calif., and set parallel to that line 120 miles apart, north to line 10 off the United States-Canadian border, and south to line 120 off Point Eugenia, Baja California. They were plotted to extend 30° southwest of lines of latitude, thus perpendicular to the coast of central California, north of Point Conception. It was intended that the 120-mile spacing would allow for additional lines to be plotted 12 miles apart between the cardinal lines and still be designated by whole numbers without resorting to fractions. However, when lines were added between cardinal lines, it was deemed sufficient to space them at 40-mile intervals. Thus, the major pattern consists of the cardinal lines in multiples of 10 ending in 0's and the ordinal lines ending in 3's and 7's. During the course of the investigations, lines were added finally to include line 157 just south of Cape San Lucas, Baja California.

The stations on the lines were laid out on the basis of a perpendicular to line 80, at a point designated station 80.60. The perpendicular, through all lines parallel to line 80, aligned the stations designated as 60's.

Most of the original stations shoreward and seaward from station 60 were plotted 40 miles apart, which allowed stations between the 40-mile points to be plotted as close as 4 miles apart and still retain whole numbers. In most cases, stations between the 40-mile points have been only 20 miles apart. Those closer than 20 miles, e.g., inshore or near islands, were so placed simply because a 20-mile spacing would have placed a station on land and the omission of such a station would have left too large a space between

the last plotted station and the land. Closer spacing than 4 miles, using fractions for station numbers, has been resorted to in some instances, e.g., to locate the eggs of the increasingly rare Pacific sardine during the peak of its spawning season.

DATA COLLECTION

The Research Vessel

A vessel used to collect oceanographic data should be a relatively stable platform at sea and be capable of reasonably rapid coverage of large areas for long periods of time. Today, most vessels used for biological and hydrographic research on the high seas are 100 or more feet long, powered to cruise at 10 to 15 knots, and capable of staying at sea for 14 to 30 days. Some ships are of multipurpose design in that they can collect plankton and hydrographic data and convert to fishing operations to handle large fishing nets, trawls, seines, etc.

Gear common to the collections of plankton and hydrographic data are power winches equipped with high-strain wire, an over-the-side platform for handling gear clear of the ship's side, and a weight at the end of the wire. Shipboard facilities should include sheltered spaces for laboratory work and adequate storage spaces for gear and samples.

Essential gear for the collection of plankton are fine mesh plankton nets with detachable cod ends, rings to keep net mouths open, a bridle assembly to tow the nets, a cable clamp to attach a lead line to the towing cable, an inclinometer to measure angles of stray during a net tow, and flowmeters to measure water volume strained by the nets.

Some of the gear described here have specifications included in figure captions for which simple descriptions will suffice to allow duplication without need for further details. Some are purchased from their manufacturers or distributors. Others have specifications too detailed to be included here. Table 1 lists all of the gear and materials described, the figures in which they are illustrated, and the places of their descriptions, and/or sources of specifications and suppliers.

The winches used for plankton tows or hydrographic casts should be electric or hydraulic and

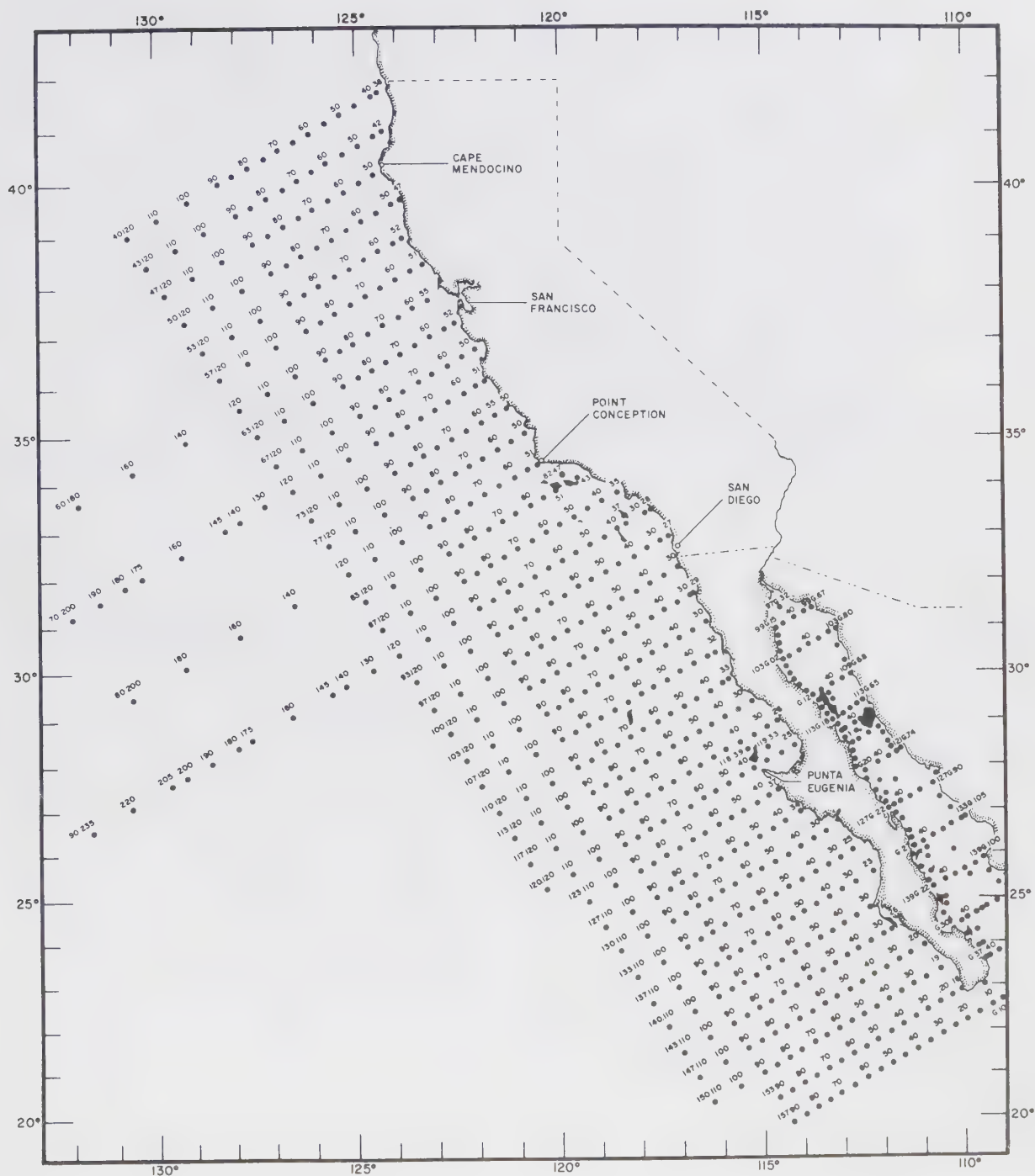


Table 1.—Gear and apparatus used for the collection and processing of data on fish eggs and larvae in the California Current region.

Gear or apparatus	Figure	Description, specifications and/or source
Collecting Plankton		
Hydrographic winch, wire, boom, block	2, 3	Described in text.
Overside platform ("bucket")	4, 5, 12	Described in text.
Weight	4	Use described in text. Specifications in figure legend.
Plankton nets	6, 13	Described in text. Specifications available from NMFS, SWFC, La Jolla.
Net rings	6	Specifications in figure legend.
Bridle assembly and lead line	6	Specifications in figure legend.
Cod end	7	Described in text. Specifications available from NMFS, SWFC, La Jolla.
Adapter-cod end to net	7	Specifications in figure legend.
Flowmeter T.S-Flowmeter (4-blade, 4-dial)	6, 13, 15, 33, 34	Source of Supply — CM ² , Inc., Mountain View, Calif., U.S.A., or Tsurumi Precision Instrument Co. (T.S.K.), Yokohama, Japan.
Inclinometer and telemetering circuitry	3, 8, 9	Use described in text. Specifications available from NMFS, SWFC, La Jolla.
Cable clamp	12	Described in text. Source of supply — Scripps Institution of Oceanography, Research Support Shop. Available as illustrated or with 2 bolts and eyes. When ordering specify cable size for which grooves will be drilled by supplier.
Tow data sheet	10	Specifications in figure legend.
Carboy for formaldehyde	16	Described in text. Available from scientific supply houses.
Plastic syringes w/automatic double valve and cannula Becton, Dickinson (B-D) Yale Luer Lok syringe (20- and 50-ml) B-D Automatic Double Valve for 50-ml syringe B-D Cannula for 20-ml syringe	16, 17	Described in text. Available from surgical supply houses.
Inside and outside labels for plankton samples	18	Specifications in text and figure legend.
Processing Plankton and Data		
T-guide and float to measure plankton volume	21, 22	Specifications in figure. Use described in figure legend.
Nylon-mesh draining cone used to measure plankton and drain before sorting	23	Described in text and figure legend. Specifications available from NMFS, SWFC, La Jolla.
Plastic cylinder to measure preservative	23, 24	Specifications in figure legend.
Microscope, Research	25	Available from scientific supply houses.
Measuring rule for fish larvae	--	Described in text.
Board for calibrating flowmeters	33, 34	Specifications in figure legend.

with drum capacities of at least 30,000 ft (9,000 m), 3/16-in (5 mm) steel wire with a strain capacity of approximately 22,000 lb. (10,000 kg)—Figure 2. Some winches may be

capable of handling conductor cable for telemetering data from all depths to which gear may be lowered. The NMFS research vessel, *David Starr Jordan*, is so equipped, with its standard

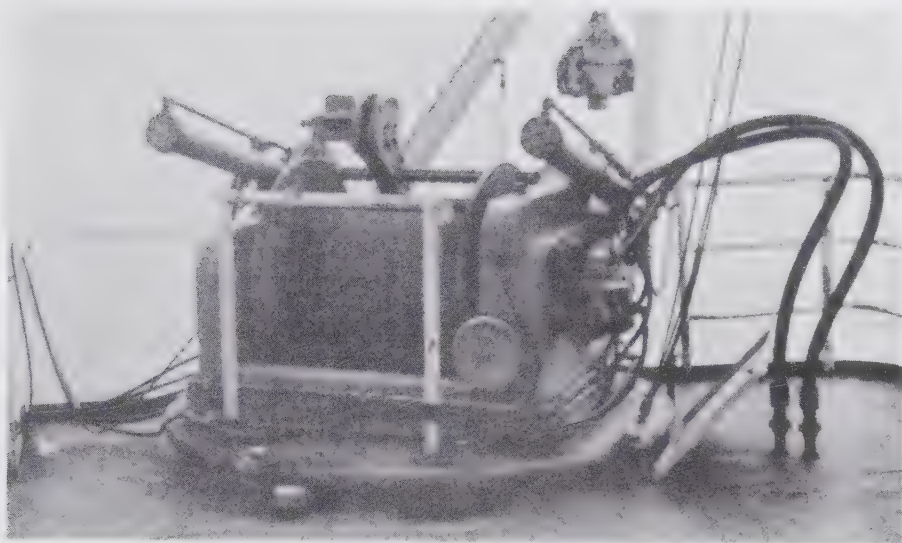


Figure 2.—Starboard winch on NMFS research vessel *David Starr Jordan* used for plankton tows and Nansen bottle casts (see Table 1). Details on drum size, wire, boom, and block are described in the text.

hydrographic winch starboard and its conductor-cable winch apart. Additional winches for trawling operations or very heavy gear are located below decks with their wire coming above decks to be fairlead astern to a powered H-frame and a stern ramp. Although the hydrographic-net tow wire is capable of the strain noted above, the boom supporting it (Figs. 2 and 3) can and need only support 5,000 lb. (2,200 kg). The block (Fig. 3) through which the wire is run also is capable of supporting 5,000 lb. and has three wheels of which one is a tensiometer.

To enable handling gear clear of the side of the ship, an overside platform (the "bucket")—Figures 4 and 5—is another essential aid to data collection. It may be designed to be swung laterally outboard as on the *Jordan* or swung upward and outboard onto a ship's rail to be fastened and kept there while at sea. The bucket is constructed of heavy steel, and its bottom is usually a steel grill which can drain immediately if water is shipped into it. A 100-lb. weight (45 kg)—Figure 4—is always attached to the end of the cable to aid in lowering the plankton net and the hydrographic cast of Nansen bottles.

Laboratory space on a research vessel may be of varying degrees of sophistication in size and

equipment. On a small ship, one space may serve for all functions but must be of sufficient size to accommodate a number of Nansen bottles with thermometers and space to read them, an area with running salt and fresh water and sink for preserving biological specimens and an area for preserving water samples and determining their chemical constituents.

A survey for plankton sampling, extending to 14 or more days, will yield large numbers of biological samples for processing ashore. Adequate storage facilities must be available to keep them until off-loaded.

The Plankton Tow

The objective of the plankton tow is to obtain qualitative and quantitative samples of the zooplankton to the depth sampled at the time and place of the tow. Most important to the objective are the proper readings and recordings of the flowmeter, the recordings of the various parts of the towing times and wire angles, the necessity for the smooth paying out and retrieval of the net, rinsing the net, and the preservation and labelling of the sample.



Figure 3.—View of boom and block, upper left (also see Fig. 2), on R/V Jordan. Plankton net tow in progress. Telemetering inclinometer (see also Fig. 8 and 9), used to indicate wire angles, hangs from towing wire. Slack in wire indicates that the net is being lowered. Man on right is the winch operator at winch console, close to rail where he can watch net operations during launching and retrieval. Man on left will record wire angles when net is retrieved (see plankton tow procedure).

THE GEAR

Plankton nets.—The quantitative plankton collections of the CalCOFI are made chiefly with nets which retain organisms ≥ 500 microns and ≥ 333 microns.

Note: Most CalCOFI plankton tows were made with a 1-m silk or nylon net (ca. 0.5-mm. mesh). The directions for the tow indicate possible single or double rig.



Figure 4.—Weight (100 lb. = 45 kg) being swung over-side at end of towing cable. The weight is a cast-iron tapered cylinder $7\frac{1}{2}$ inches (19.0 cm) in diameter, 13 inches (38 cm) high with its taper beginning about 9 inches (22.8 cm) from the bottom. One-inch (2.54 cm) stock is anchored in the casting and an eye, $1\frac{5}{8}$ -inch (4.5 cm) I.D., of the same stock is welded to it. After casting, the unit is heavily galvanized. The diameter of the eye is enough to take a strong shackle and a heavy line through it. Note swivel between the shackles which keeps the weight from twisting the wire. Casing, partially shown at lower right, is used to store the weight when not in use. Overside platform at left (also see Fig. 5 and 12) shows grill floor (description in text).



Figure 5.—Overside platform (‘bucket’) described in text, (also see Fig. 4 and 12), used to facilitate handling gear over water and away from side of ship. (The net is the Soutar-Hemingway Animal Trap (SHAT) used for vertical tows; it is not used or described here for standard collections for CalCOFI egg and larva data.)

Smith¹ described the plankton nets used on the surveys in this region and their history of design and material changes from 1939 to 1969. The standard CalCOFI nets presently used have 1/2- and 1-m mouth openings and are made of nylon mesh (see Table 1 for source of net specifications and Fig. 6 for description of mesh

¹ Smith, P. E. Plankton sampling nets and their data on surveys off California and Baja California since 1939. (Unpublished manuscript.)

sizes and assemblies for making plankton tows with either or both nets). The detachable cod end, also of nylon mesh, in which plankton is concentrated during a tow is illustrated and described in Figure 7 (source of specifications, Table 1). The adapter to couple the cod end to the net is described in the caption of Figure 7.

Note: Captions in Figures 4, 6, and 12 emphasize need for swivels in the gear train, usually close to the apparatus, to avoid twisting or unlaying wire or lines.

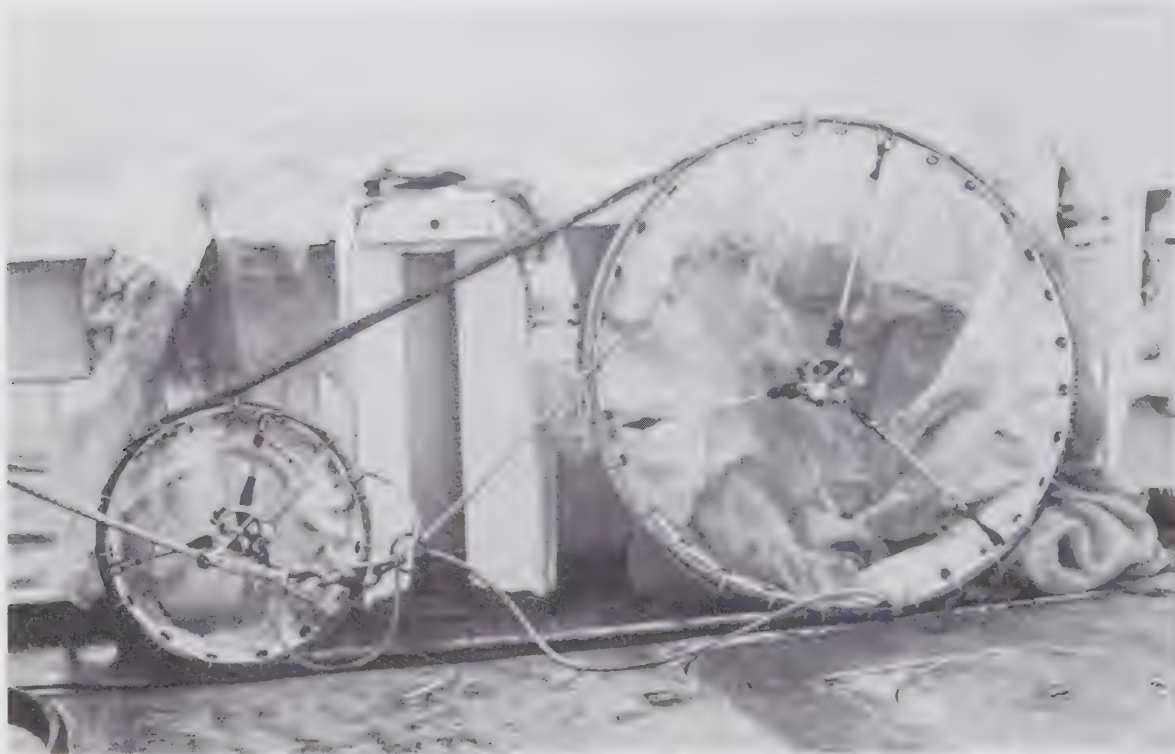


Figure 6.—Standard CalCOFI nets, 1-m mouth opening, 505- μ mesh throughout, and 0.5-m mouth opening, 333- μ mesh throughout (see Table 1 for source of specifications). Detachable cod ends are described in Figure 7. Flowmeters (see Table 1 for source of supply) are suspended in the mouth opening (also see Figures 13 and 15) by cloth-covered rubber shock cord. The cord is permanently attached to small metal eyes welded to the mouth rings.

Attachment to the lugs of the meters are by means of brass snap hooks. The net rings and braces between them are 1-inch I.D. (25.4 mm) galvanized pipe. Large ring is 1 m I.D., small ring is 0.5 m I.D. Nets are tied to the rings with 1/8-inch (4 mm) cotton cord. The three-way bridle is made up of 1/2-inch (12.7 mm) line (hemp, nylon, or diamond-braided polyethylene). Apex of bridle is a 2- or 3-inch I.D. (51 or 76 mm) steel ring of 3/8-inch (9.5 mm) thickness. The apex is 1 m away from the frame when the lines are stretched evenly. (*Note:* The points of attachment of the bridle to the rings must be no farther apart than shown. If greater than shown, the strain during any tow might bend the pipes to which the rings are welded.) The lead line, usually nylon or hemp, is 3/4- to 1-inch (20-25.5 mm) diameter for easy grasping when pulling nets aboard. (*Note:* A swivel should be attached between the lead line and the apex of the bridle and another swivel located at the cable clamp—(see Fig. 12).

If either net is used alone (see Fig. 14) as has been the case in many years of CalCOFI tows with the 1-m net, the same size rings with the same specifications are used with a three-line bridle attached at equal distances on a ring. For the 0.5-m net a lighter lead line may be used, e.g., 1/2 inch (12.7 mm).

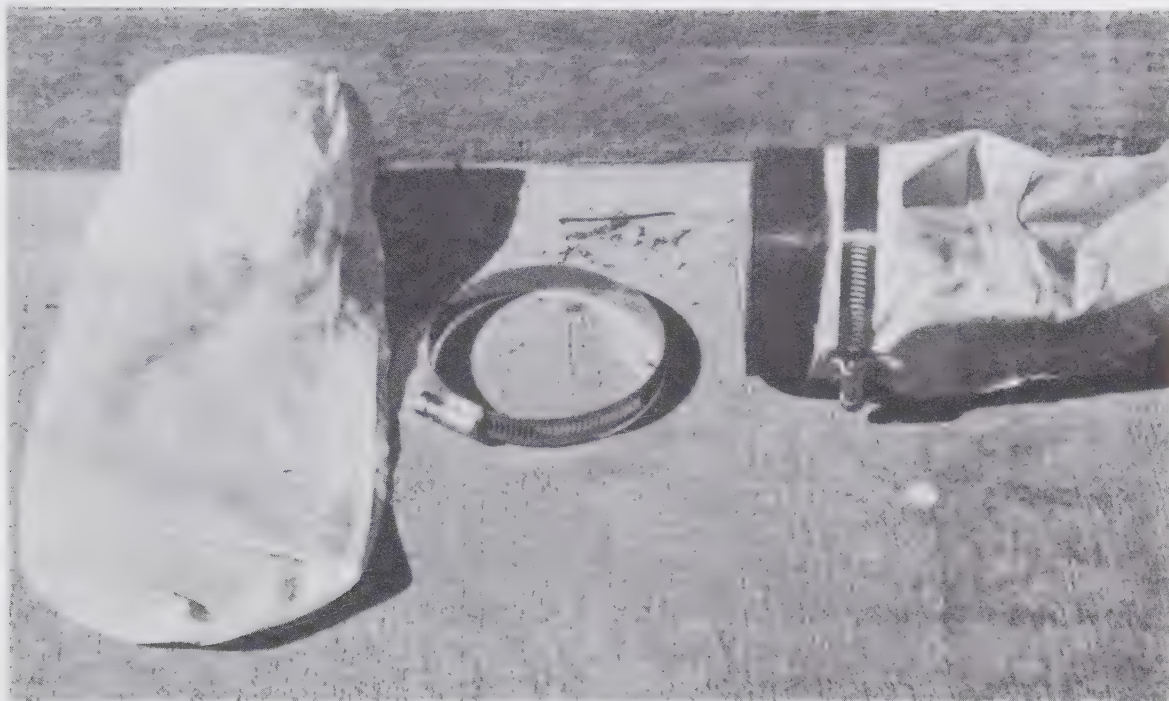


Figure 7.—Cod end (left)—(see Table 1 for source of specifications) used to concentrate plankton collected by net, detached from plankton net (right). Both are fastened with hose clamps to an adapter made of polyvinyl chloride (PVC) pipe. The pipe is approximately 4 inches (127 mm) long, 3-1/2-inches (95 mm) O.D. with 1/4-inch (6.5 mm)-thick wall. It is turned down about 3/32 inch (2.5 mm) along its length leaving flanges at each end to keep hose clamps from slipping off during tow; dimensions are not critical when turning the pipe.

Flowmeters.—When the data on plankton are processed, plankton volumes are calculated as ml/1,000 m³ of water strained (see section on standardizing data). Water strained through the net is measured by a flowmeter suspended in the mouth of the net (Figs. 6 and 13)—see Table 1 for type of meter used and source of supply. The meters are calibrated according to the methods described below in the section on standardizing data.

Inclinometers.—The CalCOFI standard plankton tow is taken by lowering the net(s) to the desired depth and retrieving it at a given rate while the ship maintains a speed that keeps the tow wire at an angle of 45°. The instrument that measures the angle of stray, the “wire angle”, is a quadrant called the inclinometer (Fig. 8) which, when hung on the wire (Fig. 3), can be monitored to record the wire angles and to regulate the ship's speed to keep the desired angle.

Two kinds of inclinometers have been used.

The one shown in Figure 8 (see Table 1 for source of specifications) is equipped with a telemetering device modified by Charles W. Forrester¹, Master of the research vessel *Jordan*. When equipped for telemetering, the angle of stray can be controlled from the bridge or engine room where wire angles are indicated in microamperes (Fig. 9). Wire angles on the quadrant (Fig. 8) are recorded on the tow sheet by an observer on deck. The second kind of inclinometer is simply one without the telemetering device. In this case, an officer of the watch or the recorder observes the wire angles during the tows and signals the bridge or engine room if the desired angle is not being maintained.

PROCEDURE FOR PLANKTON TOW

The data sheet.—When the gear is assembled as shown in Figure 6 and the data sheet for the plankton tow is prepared, the tow is ready to

¹ Originally designed (a portable unit) by Daniel M. Brown, Scripps Institution of Oceanography, La Jolla, California.

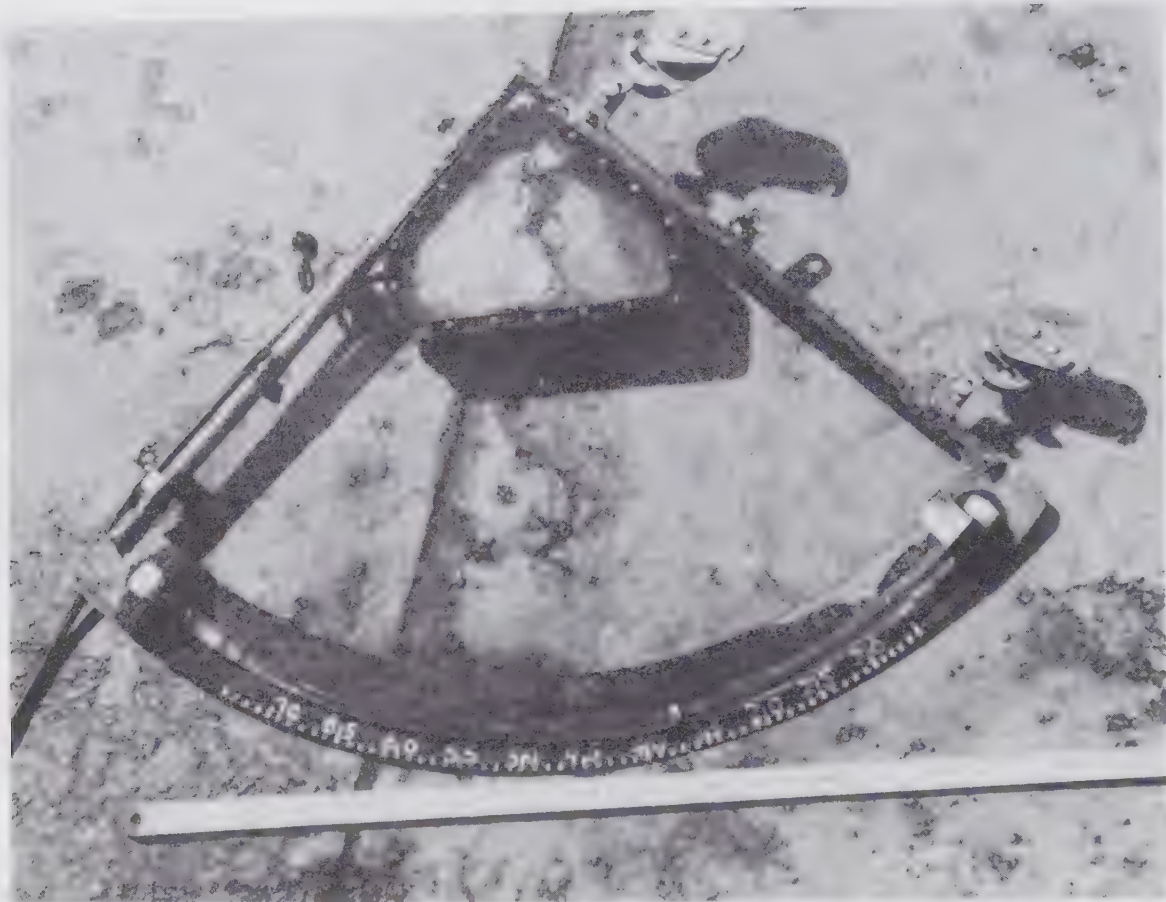


Figure 8.—Inclinometer used to measure the angle of stray, wire angle, of towing cable during plankton net tow (also see Figure 3 where pendulum indicator is more clear; see Table 1 for source of specifications).

begin. The data sheet used here for the plankton tow (Fig. 10, specifications in figure legend) is preprinted to record data for tows up to 300 m of wire out. Twenty items are numbered for automatic data processing.

The tow.—Before the net-tow station is occupied, the following numbered items should have been recorded on the data sheet.

1-Cruise, 3-Date, 4-Order occupied, 5-Station, 11-Net number (regular and/or fine) this is usually the mesh-size number (see Fig. 10), 12-Meter number (regular and/or fine), 14-Carry-over, initial meter reading (regular and/or fine).

The net tow is made off either side of the ship as follows: (Tows off the stern are not rec-

ommended because of turbulence from ships' screws.)

1. The ship is stopped; the station depth is requested from the bridge and recorded in the lower left hand section of the data sheet.

Note: With 300-m wire out, and the wire angle at 45° , the net is approximately 210 m deep. (Wire out $\times$ cosine of $45^\circ = 0.707 =$ net depth.) If station depth is less than 130 fathoms (238 m), a "Depth-of-Tow" graph (Fig. 11) is referred to in order to determine the proper amount of wire to pay out so that the net and gear will not hit the bottom. Shallow and deep tows are payed out and retrieved at the same rate as routine standard tows.

For shallow and deep tows, other than routine (items 20-22), the section 20'-22' should be used, recording lengths of wire out in decrements of 10, as called by the winch man, and wire angles (see below, procedure for tow, item 7a) at such calls.



Figure 9.—Microammeter (lower left) on console in wheelhouse to indicate angle of stray registered by the telemetering inclinometer shown in Figures 3 and 8 (see Table 1 for source of specifications). "0" indicates the desired 45° wire angle. "200 left" is 5° increase — 50° on inclinometer. "200 right" is 5° decrease — 40° on inclinometer.

The zeroed meter (lower right) is synchronized with the meter on the deck console (see Fig. 3) enabling the officer on watch to know the amounts of wire out at the same time as the deck force making a net tow.

2. The flowmeter is read and checked against the recorded initial meter reading—item 14. If there had been a previous tow, this should have been the final meter reading—item 13 on the previous tow sheet. If the reading changed between tows, the last recording is *crossed out*, the new reading entered, and an explanation given in the Remarks section, lower right hand part of the data sheet.
3. The 100-lb. weight is lowered about 10 to 15 m below the surface of the water. If the ship is still slightly underway, the wire is pulled to the side of the bucket and fastened close with snap hook attached to the outside of the bucket (Fig. 12).
4. The bridle clamp (Fig. 12)—see Table 1 for source of supply—is fastened tightly to towing wire, and a safety chain or line (Fig. 12) is fastened to the wire above the clamp. The clamp should be about 15 to 20 m above the weight, less in shallow water

(see Depth-of-Tow graph—Fig. 11—for directions concerning weight in shallow tows).

5. The inclinometer is fastened to the wire above the clamp. Enough slack is left on the line to the inclinometer so that when the proper angle is achieved during tow (Fig. 3), it will not ride up on the cable to hit the block. (If the survey is for net tows only, the inclinometer may be left "permanently" on the tow wire. It is always removed if a hydrographic cast has to be made with the cable.)
6. The cable clamp is lowered to the sea surface, and the winch meter is zeroed.
7. The ship is set underway, wind off the bow on the side on which the tow is taken., and the signal to start the tow is given from the bridge. The block or pin, which keeps the blades from revolving between tows, is removed from the meter(s), and the net(s) is thrown into the water (Fig. 13). (Some

1 CRUISE 6907-J		2 OCCUPANCY CODE REG. 05 FINE		3 DATE VII-21		4 ORDER OCCUPIED 48		5 STATION 80.52		6 HOUR (PST) 0220 TO 0241 30	
TIME		MESH		REG.		FINE		THIS SPACE FOR OFFICE USE ONLY: INSTRUCTIONS TO KEYPUNCH OPERATOR.			
11 SINKING: 6 '02		11 NET NO.		535		333					
12 TOWING: 15 '28		12 METER NO.		1504		1177					
		CARRYOVER		35		35					
13 TOTAL: 21 '30		13 FINAL		90538		17180					
14 AMT. OF WIRE OUT 300 METERS		14 INITIAL		84500		11330					
		15 DIFF.		6038		5850					
16 TOTAL NO. OF ANGLES 30		ACCEPTED POSITION		16 30° 24.3' N		17 120° 36.5' W					
		LATITUDE		LONGITUDE							
ROUTINE: TIME NET ENTERS WATER: 0220											
18 ANGLES	49	48	47	46	47	43	48	47	47	47	
WIRE OUT	300	290	280	270	260	250	240	230	220	210	
19 ANGLES	46	46	48	48	46	45	47	48	48	46	
WIRE OUT	200	190	180	170	160	150	140	130	120	110	
20 ANGLES	45	47	49	48	46	45	46	47	45	50	
WIRE OUT	100	90	80	70	60	50	40	30	20	10	
OTHER: TIME NET ENTERS WATER: _____											
21 ANGLES											
WIRE OUT											
22 ANGLES											
WIRE OUT											
23 ANGLES											
WIRE OUT											
NO. OF JARS REG. 1 FINE 1		WIND 310° 10		SKY (CONDITION) NIGHT		REMARKS:					
INCHES OF PLANKTON REG. 4 FINE 1 1/2		SEA (CONDITION) CALM		SWELL NIGHT		MANY SMALL SAVY					
FORM. & BORATE ADDED REG. DK FINE DK		NET CLOGGING (CHECK ONE)		MODERATE		HEAVY		AROUND SHIP.			
SAMPLE LABELED REG. DK FINE DK		NET WASHING (CHECK ONE)		RINSED		WASHED					
DEPTH 163 FATHOMS		NONE		BEFORE STA.		AFTER STA.					
		RIPS & HOLES IN NET		WHEN MENDED		BEFORE STA.					
		LOCATION:		WHEN MENDED		BEFORE STA.		OBSERVER: KRAMER			

Figure 10.—Plankton-tow data sheet.—A sample copy of a sheet made out for station 80.52 on cruise 6907-J (see text). The sheet is a water-resistant linen designated "36-lb. ledger." Other qualities of paper, not so designated have been found to deteriorate when wetted by rain or handling. The sheets are delivered in pads glued at one end. When readied for use, two sheets at a time are torn off, a carbon paper inserted between them, and all are placed on a clipboard and held at the bottom of the sheets by a heavy rubber band.

meters have "automatic" blocks that release the impeller blades when water flows through them.)

- a. The stop watch is started when the flow-meter(s) is seen to sink below the surface of the water.

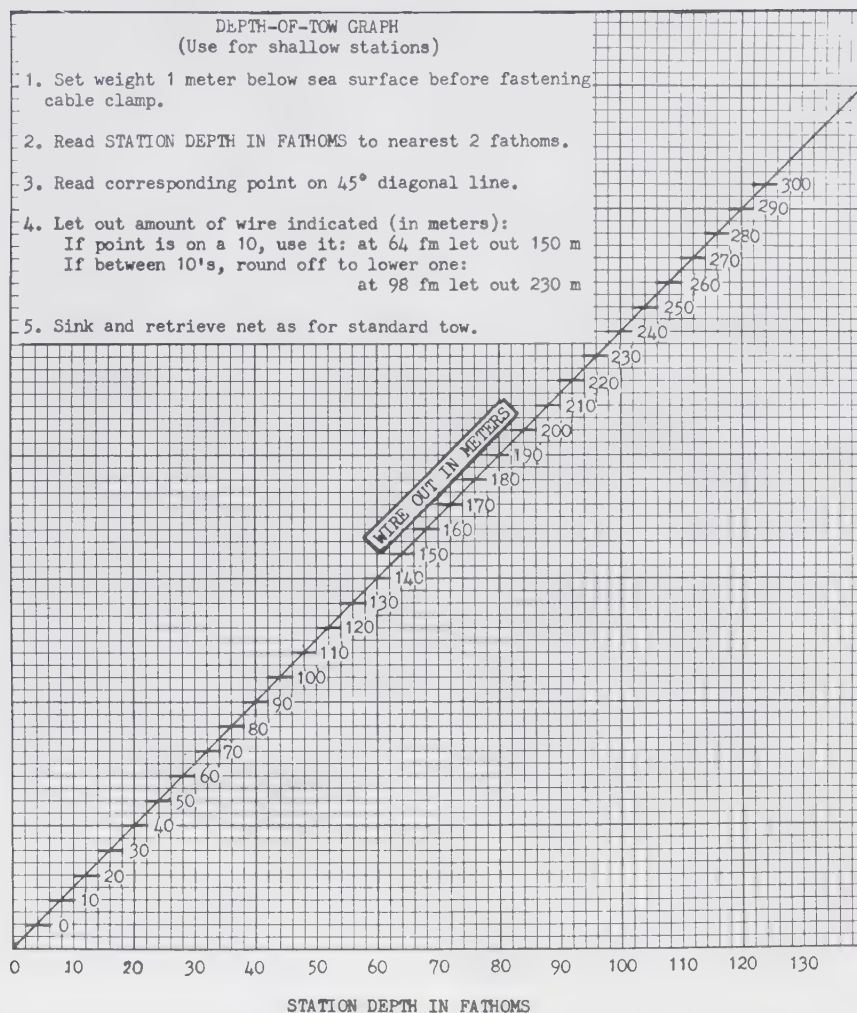


Figure 11.—Depth-of-tow graph.—To be used if station depth is 130 fathoms or less when standard tow is 300 m wire out. If standard tow is less than 300 m wire out, e.g., 100 m or 200 m, the graph is still applicable. For 100-m standard tow, use graph when station depth is 45 fathoms (82 m) or less. For 200-m standard tow, use graph when station depth is 165 fathoms or less. Except for the very shallow depths, 20 fathoms or less, where a tow is practically all at the surface, the points on the diagonal line indicating the amounts of wire to be paid out are calculated to keep the net approximately 10 to 18 m off the bottom. This is considered a safe margin, and it is recommended that no changes be made when one considers that only the rocking of a ship in heavy seas can reduce an 8-m safety margin to 5 or 3 m.

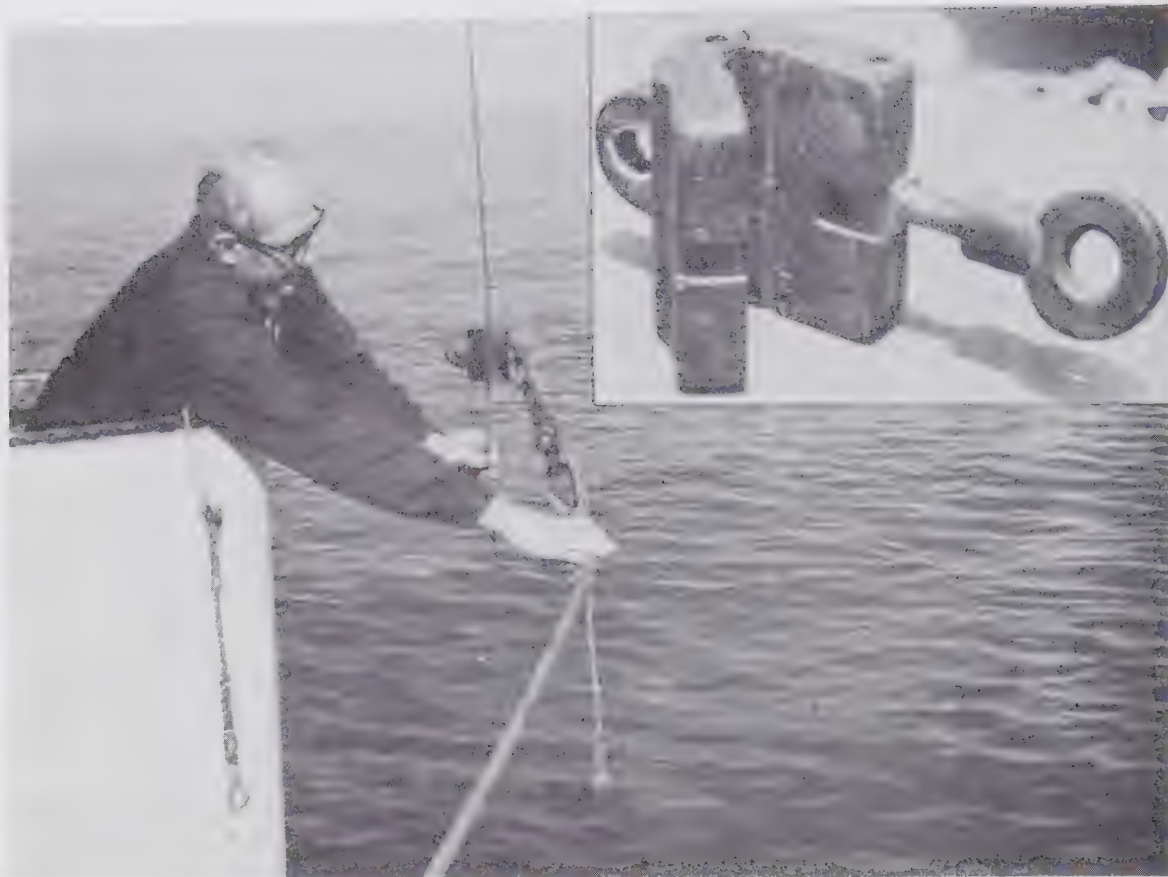


Figure 12.—Cable clamp attaching plankton net lead line to towing cable. Clamp is tightened (and loosened) with a steel rod (suspended in bucket) inserted into bolt eye. Insert: cable clamp, opened, showing grooves to accommodate cable. (See Table 1 for source of supply). Note swivel between the two shackles (see legend for Fig. 6). Small line hanging below man's right hand is the safety line to be hooked to the towing cable above the clamp. Line with hook hanging at side of bucket is used to retain the towing cable, *after* the weight is lowered, if the ship has a slight way-on so that clamp and inclinometer can be attached.

- b. The net(s) is allowed to stream out (Fig. 14) before lowering, and when it is obvious that it is not tangled, the wire is payed out at 50 m/min until the desired depth is reached.
- c. At the desired depth, the watch is stopped, sinking time is recorded (item 8), and *watch zeroed and restarted immediately*.
- d. When the watch is restarted the net(s) is left at the desired depth for 30 sec (hypothesized that a "falling" net(s) will straighten out at depth in the 30-sec interval).
- e. At the end of 30 sec *the watch is not stopped*, the angle is recorded for that depth, and retrieval is begun at the rate of 10 m per 30 sec. The angle is recorded at every 10 m in items 20-22 (Routine) or 20'-22' (Other).

Note: Since the net is "fishing" on the way down, sinking time is as important as that of retrieval.

Recording the time is simplified if "Time Net Enters Water" is recorded to the nearest 5 min. (This is the item near 20—or 20'—Routine or Other, depending on tow—see later). This time is also recorded at item 6.

Note: Ship speed, during sinking, times at depth, and during retrieval, is maintained to keep the wire angle at 45°. In dead calm, it may be necessary to run the ship in circles to maintain the wire angle.

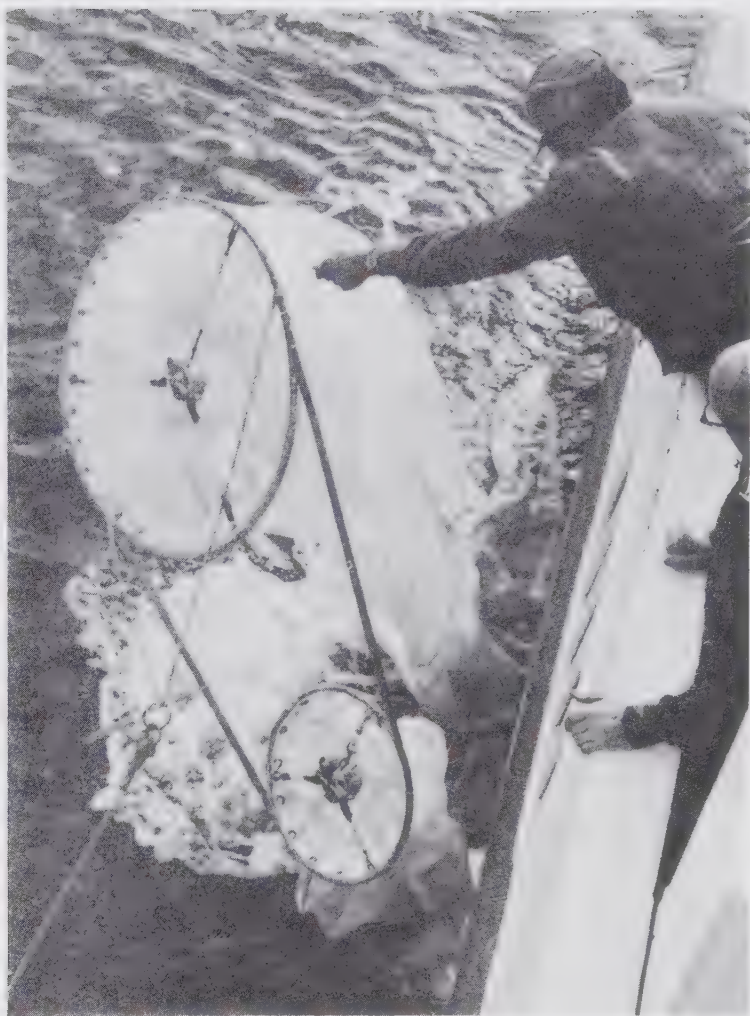


Figure 13.—Launching 1/2- and 1-m nets to begin standard CalCOFI plankton tow.

- f. The net(s) is brought directly out of the water at a steady rate. When the flow-meter(s) breaks the surface the watch is stopped. Its reading is the towing time (item 9).
8. The net(s) is rinsed to get all the plankton into the cod end, keeping the cod end(s) dangling and the net ring(s) at rail height (Fig. 15). The net(s) is brought aboard (Fig. 6), and the cod end(s) removed, keeping the plankton sample(s) from spilling back into the net(s). The plankton is preserved immediately
9. The plankton is poured from the cod end into a jar of appropriate size, usually a quart. The cod end is rinsed down to gather the last of the plankton at its bottom. When fairly well drained, the cod end is everted over and into the jar, and the remaining plankton washed off carefully.
10. The preservative (50 ml full-strength formaldehyde per quart) is added (see note below) when the jar is at least three-fourths full of seawater plus plankton in order to avoid "burning" the delicate planktonic organisms. Buffer to counteract the



Figure 14.—Streaming net just before lowering (see text). This is a 1-m net only.

acidity of plankton in Formalin is added—20 ml per quart—(saturated solution of sodium borate in seawater). The jar is filled almost to the top with seawater, capped, and shaken to insure a good mixture of preservative and plankton.

Note: Full-strength formaldehyde aboard ship is kept in 5-gal polypropylene carboys (see Table 1 for source of supply). With the carboy moored securely above the sink (Fig. 16), the preservative is drawn by siphon action. A further safety measure now adopted is to draw the formaldehyde via a teflon tube into a 50-ml plastic syringe through an automatic double valve (Fig. 17)—see Table 1 for source of supply. The buffer is added with a 20-ml plastic syringe fitted with cannula (a “needle” without a point).

11. Inside and outside labels are filled out. (The greater part of these might be filled out before a station is occupied.) Inside and outside labels are illustrated in Figure 18. If more than one jar is used for a sample, labels are so designated—1 of 2, 2 of 2, or 1 of 3, 2 of 3, etc. The number of jars used

is noted in the proper space on the tow sheet (see 14d below).

12. The cod end(s) is washed (it may be left everted) and replaced on the net(s) in preparation for the next tow (Fig. 6).
13. *Before leaving station* the meter(s) is read and recorded as the final reading at item 13, and the initial reading, item 14, is subtracted from item 13.



Figure 15.—Rinsing down plankton after net tow, before removing cod end with sample. *Note:* Cod end should be removed after it is hung from the ship's rail as shown in Figure 6.

Note: Experience will teach the readers what a normal meter reading should be for a standard tow. If meter readings are not normal, the net tow *may* have to be repeated. A very high reading may have been caused by too great a ship's speed—check for many high wire angles. A low reading may have been due to too slow a ship's speed—check for many low wire angles. Another reason for low meter readings may be clogging of the nets. This may be cumulative if a net is not rinsed properly or it may occur at a single station. If a meter shows a trend toward lower and lower readings, it is not malfunctioning, and the net should be washed (see below). The net tow need not be repeated if it is obvious that heavy clogging is the reason for low readings (it will only clog again) or if the ship's speed has caused low or high angles. If wire angles are normal, the net clean, the towing time routine but the meter reading is low, the cause

could be that a bit of detritus, a fish, or even a large jelly or salp had become entangled in the meter blades for a portion of the tow. Under these conditions, the tow should be repeated. If the reading is again very low and it is obvious that the flow-meter is not functioning properly, replace the meter and repeat the tow. *Do not oil or grease any meter or make any repairs that might alter the rotation of the blades.* Repairs of this type would seriously affect the calibration of the meter.

14. The tow sheet is completed as follows:

- a. Towing time—the time at which the watch was stopped when the meter(s) broke water, is recorded at item 9.
- b. Total towing time—recorded in item 10, is the sum of items 8 and 9. In a 300-m tow, total time should be about 21'30"—6' sinking time + 15'30" towing time. If total time is off by 15 to 20 sec, it must be explained in the Remarks section. The most usual variation will be in the sinking time, caused by a slightly faster or slower rate in paying out the wire than the recommended 50 m/min. In certain conditions, such as poor control of the ship, countercurrents below the sea surface adversely controlling the net as it falls, etc., the winch operator may have to depart from the sinking-time procedures to slow the falling net in order to keep it from becoming tangled. Such departures from normal procedures must be recorded in the Remarks section.
- c. Total towing time is added, in minutes and seconds, to item 6 to record the hour, minutes and seconds at item 7. This is actually the time the net comes out of the water.
- d. Number of jars per sample—lower left hand section of sheet.
- e. Inches of plankton—this gives approximate volume before water is added.
- f. Formalin and borate added—the person who adds the preservative and buffer should initial this box for each net—*after the Formalin and borate are added.*
- g. Sample labelled—the person who labels the sample(s) should initial this box - *after the sample(s) is labelled.*
- h. Depth, wind, sky, sea swell—should be given by a crew member to the observer who is recording the angles while the tow is being taken.

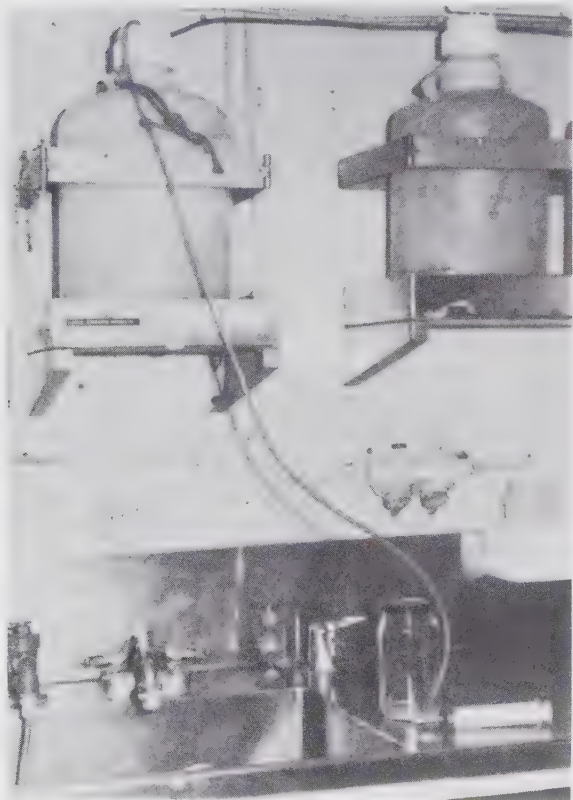


Figure 16.—Installation of 5-gal (18.91 liters) heavy-gauge plastic carboys (see Table 1 for source of supply) of concentrated formaldehyde aboard R/V *David Starr Jordan*—carboy, upper right is reserve supply. Metal straps are hinged to release carboys and locked at one corner by metal pin through the hinge. Screw-top plastic cap is holed to allow siphon action. Siphon is started by pulling formaldehyde with action of automatic double valve on 50-ml syringe, bottom right (see Fig. 17). At middle right is 20-mm plastic syringe with cannula (see Table 1 for source of supply) and a 1-quart jar containing saturated solution of sodium borate in seawater (see text for buffering plankton samples).

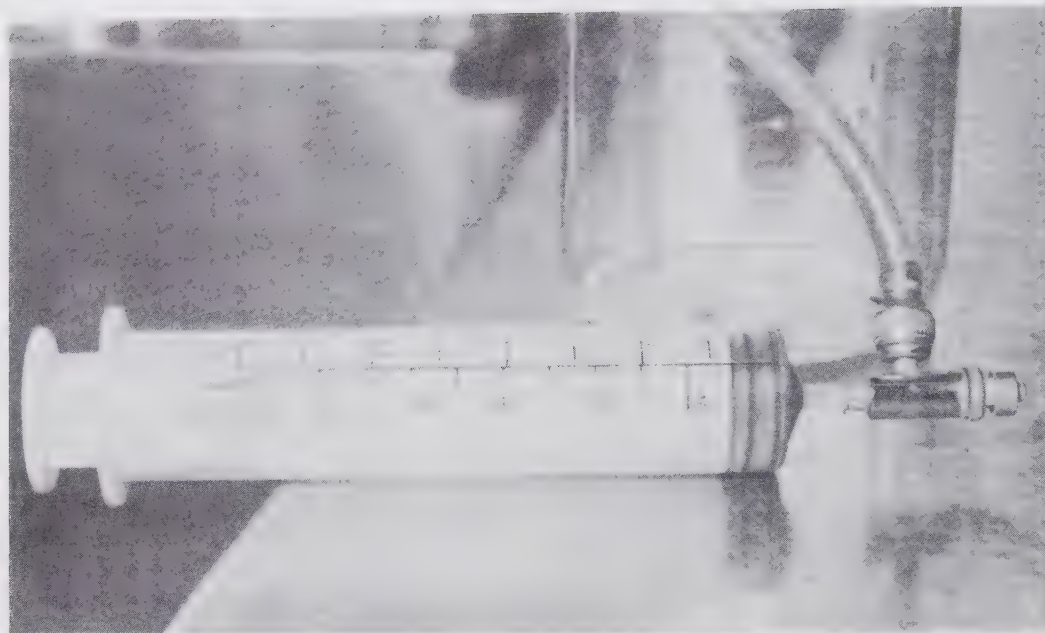


Figure 17.—Two-way, double action valve on syringe (see Table 1 for source of supply). Usually the valve is fixed to the syringe by a screw-on action. In this illustration, the valve is fitted tightly by friction to a disposable plastic syringe.



Figure 18.—Labels for plankton samples. Clockwise from upper left—Tie-on cardboard label on 1-quart (1 liter) bail-type jar; screw-on cap labeled with Martek pen, on 1-pint (1/2 liter) jar; self-adhesive label on screw-on cap; inside label on which information duplicates (not in any of these cases) whatever is written on an outside label. Inside label is made of 32-lb., chemically resistant linen called "Resist-all."

- i. Amount of clogging—should be checked in one of the appropriate boxes. This is best observed by noting the variation of the meter readings (see 3b above). If washing is needed, one of three methods may be used: (1) The net is everted, still on its ring, and brushed down with an ordinary sweeping broom and running seawater; (2) rings are stood on edge, net is tightened along its length by tying down end (without cod end attached) and hosed down with high-pressure fire hose. This is very effective provided that plankton has not dried in the meshes; (3) net is detached from ring and put in a washing machine using a 30-min cycle, warm water (not hot) and a nonpolluting detergent.
- j. Rips and holes in the net—the net should be looked at after every tow to check on needs for repair or replacement. If holes or tears are small, they should be sewn before the next tow with nylon thread of a dark color (to be easily located for sewing machine repair later on shore). Check appropriate boxes. If

the net is torn beyond mending at sea, replace the net.

- k. Recheck sheet to be sure that all items are filled in. Nonroutine items should be included in Remarks section, e.g., odd meter readings, prolonged stops at stations, delays between stations, etc.
 - l. The accepted position, item 16, may be listed when the station is occupied or at the end of the cruise when the captain has compiled a complete list of the positions of all stations.
 - m. The occupancy code, item 2, is filled in, onshore, at the end of the cruise. This is usually one of a series of numbers used by the programmer to describe the type of tow or the station occupied.
15. The sheet is set up for the next station: items 1, 3, 4, 5, 11, 12, and 14 are entered. Item 14 should be the final reading of the preceding tow and should be rechecked before starting next tow.

Additional Data Collections

A tow for plankton is made at every station occupied during a CalCOFI survey. Additional work and data collection at each station include: Collection of meteorological data; a bathythermogram with the expendable bathythermograph (XBT), a surface temperature reading taken with a bucket thermometer, a sample of water from 10-m depth with a Nansen bottle from which shipboard analysis is made of salinity and nutrients including phosphate, nitrate, nitrite and sulphite; drift bottle releases at specified station, secchi disc reading at all day stations and Pacific saury (*Cololabis saira*) observations at all night stations.

The XBT is dropped from a launching tube, located aft near a ship's rail, to record temperature profiles to 1,000 ft (450 m) deep. The recording is made electronically in a sheltered space (laboratory, etc.) on the vessel (Saur and Stewart, 1967; Saur and Stevens, 1972). The XBT has replaced the former BT which was launched and retrieved on a cable with a small winch located aft near a ship's rail recording temperature profiles on a smoked slide to 450 or 900 ft (137 or 355 m).

PROCESSING PLANKTON AND STANDARDIZING DATA

Processing of plankton is begun at the laboratory when the collections are brought back from sea. This is carried out in several steps: Measuring the volume of plankton in each sample, sorting out and enumerating all fish eggs and larvae, identifying all larvae, measuring certain larvae, identifying certain fish eggs and staging (ageing) some, and finally, curating all fish eggs and larvae. All data are standardized (see below) and now are subjected to automatic data processing (ADP) for final analyses and publication. Two methods for standardization are described, one, the old method of hand calculation and two, the ADP which are described wherever changes have been affected, and for which a flow diagram is depicted in Figure 19.

Plankton Volume Determination

Plankton volumes are determined by displacement, (sometimes termed "wet volumes") recorded to the nearest milliliter. Two volumes are recorded for each sample:

1. Total volume—includes everything in the sample except small adult fishes, juvenile fishes, squid, octupi, and adult pelagic crabs (*Pleuroncodes*) none of which are considered planktonic.
2. Total volume minus large organisms—large planktonic organisms are jellies and tunicates whose individual volumes exceed 5 ml.

The plankton volumes for a cruise are recorded on a Plankton Volumes data sheets (Fig. 20) beginning with data from the original tow sheets, first listing all the stations occupied in their numerical order and noting the number of jars used for each sample. The plankton samples are removed from their boxes and readied for measuring their volumes by arranging them in the numerical order of stations. The procedure for determining volumes is as follows:

1. Each quart jar sent to sea is calibrated and etched with a number (see Fig. 22) that represents its total volume when filled to a level at which a mark on one device (a float) matches a mark on another (a T-guide)—Figs. 21 and 22. When the calibrated jar contains a plankton sample, the

DATA PROCESSING
FISH EGGS and LARVAE

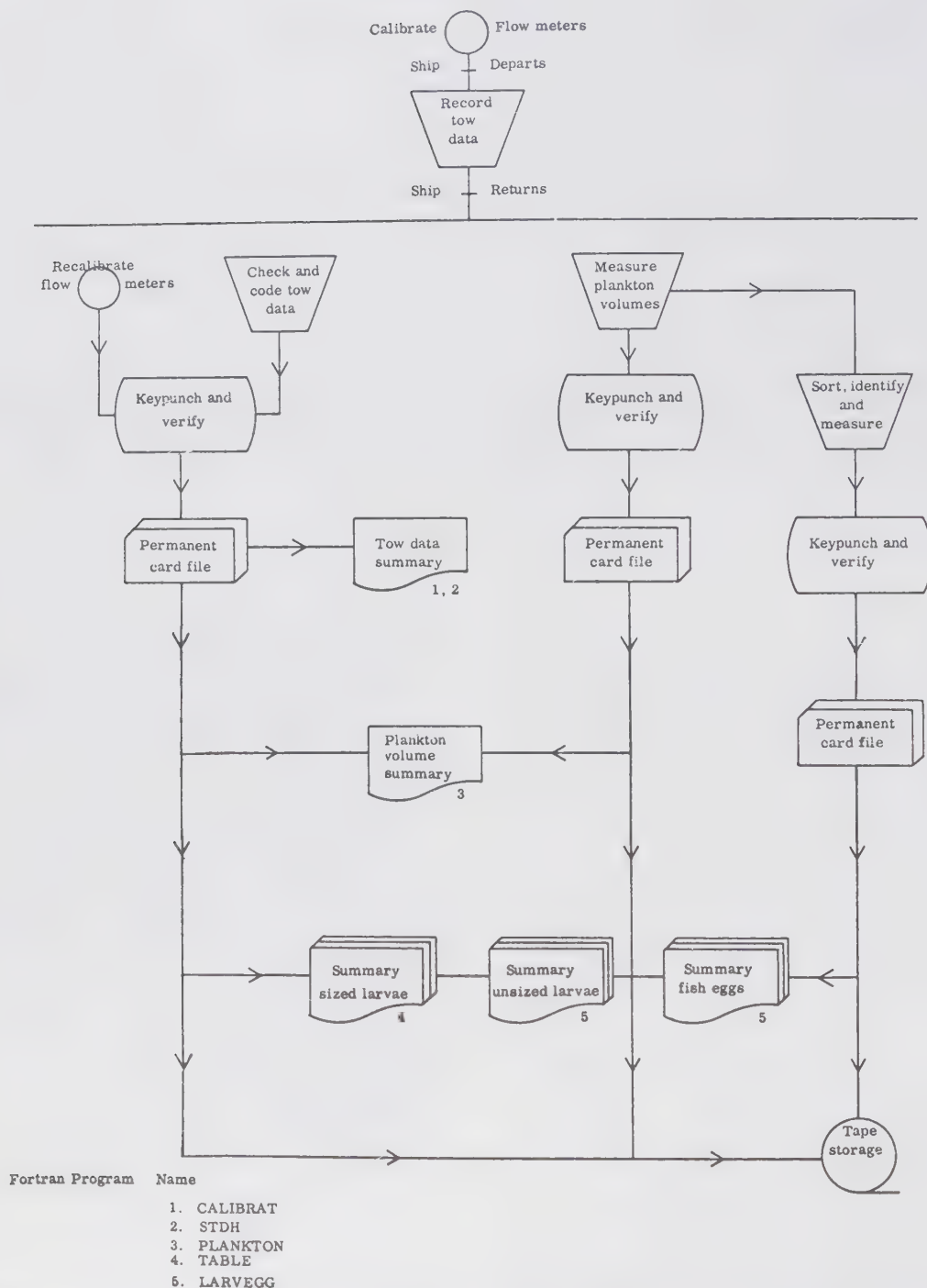


Figure 19.—Flow diagram of procedures by the National Marine Fisheries Service for the processing of plankton, fish eggs and larvae, and data through tape storage, La Jolla, Calif. (Designed by J. R. Zweifel, NMFS, La Jolla). See text for disposal of sorted samples.

Station	Ord. Ccpd.	No. Jars	Person Meas.	Total Volume	T.V.-L. Org.	% Fract.	Fractioned Samples			Person Sorting	Date Sorted	Remarks
							Vol. L	Vol. R	Vol. Rem.			
60.50	139	2		21		.50	10½	10½		RM	4-1-70	
60.55	140	2		13		.50	6.5	6.5		SGC	4/2/70	
60.60	141	2		238		.50	119.0	119.0		Pa	4/2/70	
60.70	142	2		237		.50	118.5	118.5		SGC	4/2/70	
60.80	143	2		81		"	40.5	40.5		RM	4/2/70	
66.49	138	2		31		"	15.5	15.5		SGC	6-1-70	
67.50	137	2		73		"	36.5	36.5		SGC	4-3-70	
67.55	136	2		209		"	104.5	104.5		Pa	6-3-70	
67.60	135	2		69		"	34.5	34.5		RM	6-3-70	
67.70	134	2		201		"	100.5	100.5		RM	6-3-70	
67.80	133	2		49		"	24.5	24.5		RM	6-3-70	
70.51	128	2		91		"	45.5	45.5		Pa	4-3-70	
70.55	129	2		88		"	44.0	44.0		RM	4-3-70	
70.60	130	2		137		"	68.5	68.5		SGC	4/3/70	
70.70	131	2		318		"	159.0	159.0		RM	4-7-70	
70.80	132	2		41		"	20.5	20.5		RM	4-7-70	

Figure 20.—Plankton-volume data sheet.—A sample copy of a sheet made out for stations 60.50 to 70.80 on cruise 7003—"Ogon." (This does not match any of the sets of data for which examples are shown in this report.) The data shown here were collected on a special cruise on the CalCOFI grid by a cooperating vessel, *Ogon*, of the U.S.S.R., to show fractioning of samples (no longer done at this laboratory—see note on description of Set IV in the section on processing data.) These samples were fractioned by agreement with the Russian participants in that each organization would keep one half of each sample for study at its respective laboratory and exchange the data on all samples.

first step in measuring is to bring the plankton plus its preservative to the "proper level" by using the T-guide and float as shown with Figure 22. (Alternative method—If calibrated jars, T-guide, and float are not available, the sample and its preservative are poured into a graduated cylinder and enough preservative is added or subtracted to bring the level of the liquid to an even milliliter, usually 900 or 1,000; the volume is recorded.)

2. A funnel is placed in a clean graduated cylinder (see Fig. 24 for specifications), and a 333- μ -mesh nylon draining cone (source of specifications—Table 1) is placed in the funnel.

3. The plankton and preservative in Step 1 (either alternative) are poured into the draining cone (Fig. 23). The plankton is retained in the cone while the liquid drains into the cylinder. The plankton is considered drained when the liquid from the bottom of the cone diminishes to an occasional drop. Draining time varies with the size and composition of the sample.
4. The volume of the drained liquid in the cylinder (Fig. 24) is subtracted from the initial volume of plankton plus liquid (Fig. 22)—calibrated quart jar or graduate in alternate of step 1. The difference, the total volume of the sample, is recorded on the data sheet.

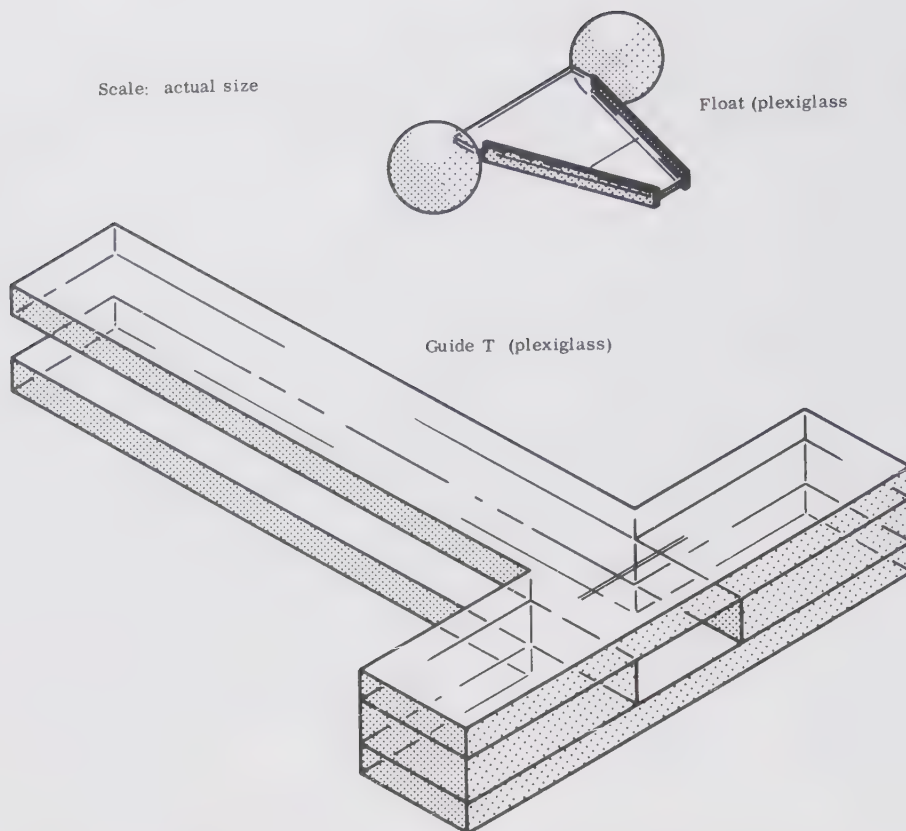


Figure 21.—T-Guide and float, actual size (designed by J. R. Thrailkill, NMFS). This is used to calibrate quart jars and to adjust volumes of plankton + preservative in measuring plankton volumes. To use: the float, triangular section pointing up, is inserted between the vertical limbs of the T-guide. The apparatus is placed in a calibrated jar of plankton plus preservative and the horizontal limbs rested on top of the jar (also see Fig. 20). Liquid is added or subtracted causing the float to move up or down until the etched line on the float is between the etched double line on the T (see Fig. 22). The coincidence of the lines indicates that the proper level has been reached, i.e., the volume, in millimeters, etched on the jar—accuracy ± 1 ml.

5. Large jellies and tunicates are removed (estimated as equal to or larger than 5 ml in volume), washed, and placed into a graduate with a known volume of 5% buffered Formalin. The difference in this reading and the known volume of added solution is the Volume of the Large Organisms which is subtracted from the Total Volume and recorded as Total Volume Minus Large Organisms (Fig. 20).
6. The drained plankton and the large organisms are put into a pint jar(s)—see Note below, and the jar(s) is filled with the original preservative. The original inside label(s) is placed in the jar(s). If a screw-

top quart jar is used at the time of collection, the same lid is used on the pint jar. If that cap was marked with a writing pen (Martek) or a self-adhesive label, it is left as is. If a string label was used, as on a bail-type jar, the top of the cap is labelled with a self-adhesive label or Martek pen (Fig. 18).

Note: Pint jars are used to store measured plankton because it has been found that almost 90% of all single-jar samples on CalCOFI surveys will fit into pint jars. Even if more than one pint jar is used for some samples, the boxes for storing this size jar require very little more than half the storage space needed for quarts.

7. Calibrated quart jars - with unmarked lids - are returned to wooden seagoing boxes (ca-



Figure 22.—T-guide in use in first step in measuring plankton volume. The jar is calibrated to 892 ml, liquid alone or liquid plus plankton. Liquid is being removed to match the etched lines on the float and T-guide (see Fig. 21 for directions for use).

capacity: 12 jars in eggcrate partitions) constructed of 1/2-inch (12.7 mm) plywood with hinged lids. If laboratory and storage space on shipboard are reasonably dry, the original cardboard containers can be used to store jars of plankton at sea.

8. Pint jars with plankton are packed in numerical order of stations into cardboard cartons, and the outside of the cartons are labelled with cruise number and numerical listing of the stations in the box stored to be visible on shelves.

Plankton Sorting

Each measured sample delivered to the sorting laboratory is sorted for all fish eggs and larvae of which all are enumerated. Some fish eggs and larvae are identified, some are scanned and categorized as "few", "many", or "abundant", and some fish larvae are measured (Table 2).

Although techniques may vary with individual sorters, the general method for sorting is as follows:

1. The plankton is removed from its preservative by straining it through a 333- μ mesh nylon draining cone (the same kind used when measuring plankton), and the plankton, with about 2 liters of fresh water plus a few drops of full strength formaldehyde, is put into a 3-liter beaker. The original preservative is kept in its original jar. Fresh water is used because it has been found that prolonged exposure to concentrations of Formalin in handling, stirring and under their eyes, even 3 to 5%, may cause sorters to become sensitive and allergic to fumes and liquid. A sample can be kept as long as 1 month in the weak solution of fresh water with formaldehyde. This does not imply that such length of time is necessary for sorting any single sample. The average sorting time is about one sample (100 ml plankton) per day per sorter.
2. The plankton is stirred and poured into a small beaker (200 ml). This, in turn, is stirred and poured into a number of syracuse dishes (ground-glass sides) from



Figure 23.—Pouring plankton and preservative into draining cone is the third step of measuring plankton volume. The cone (333- μ nylon mesh—see Table 1 for source of specifications) retains the plankton; the cylinder receives the fluid. Large sewing needles suspend cone in funnel keeping mesh from touching funnel's sides and allowing proper drainage.

which the organisms will be sorted. These dishes are aligned on one side of the microscope. On the other side of the microscope are a number of syracuse dishes, each labelled on its ground-glass surface with the name of the organism which will be transferred to it when sorted (Fig. 25). Each of the labelled dishes is about half full of 3 to 5% buffered Formalin. (In this instance, the few dishes of such Formalin are not enough to affect the sorters adversely.)

3. Using a binocular, dissecting microscope, usually at a total of 9X power, with trans-



Figure 24.—Reading volume is the fourth step of measuring plankton preservative after plankton has drained to an occasional drop. The volume of the calibrated jar, holding plankton and preservative (Fig. 20), less the volume in the cylinder equals the displacement volume of the plankton. The cylinder is plastic tubing, 1-1/2 inches I.D. $\times$ 34 inches long (3.8 $\times$ 86.4 cm) with graduations etched on the cylinder or on a grooved board, as illustrated. The graduations on cylinder or on the board are 5-ml units from 0-600 ml and 2-ml units from 600-910 ml. Volumes are read to the nearest millimeter.

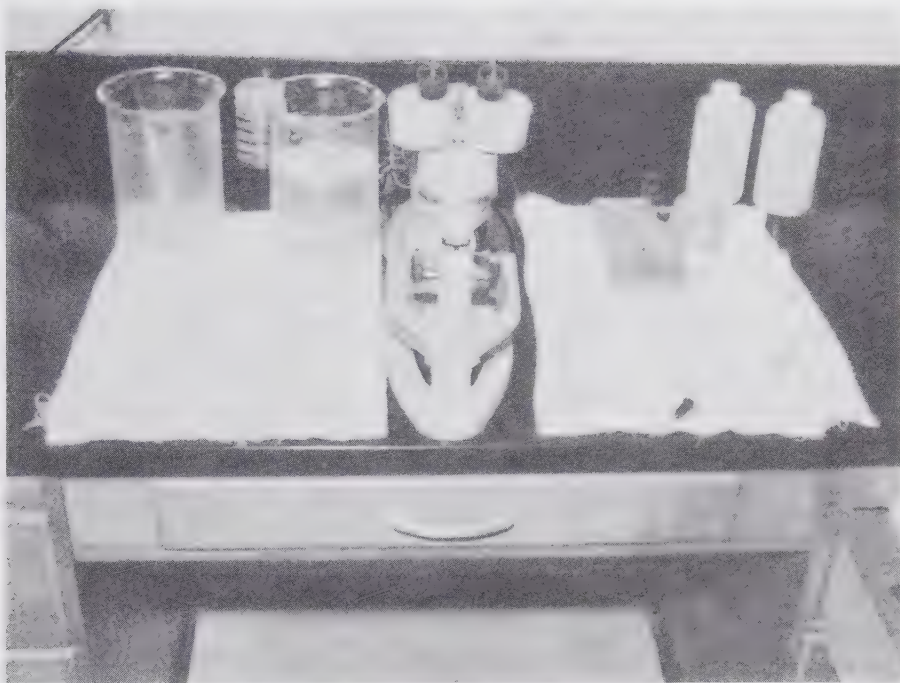


Figure 25.—Arrangement of plankton sorter's work. Unsorted plankton on left side of microscope, sorted organisms on the right. (See text for procedures.)

mitted light, all fish eggs and larvae are picked out with pipettes and fine quality (stainless steel) forceps and transferred to their appropriately labelled dishes.

Note: Research quality microscopes are used because any of inferior quality would be detrimental to the eyesight of persons engaged in this type of week-long work for 6 to 8 hr per day.

4. When the fish eggs and larvae are sorted from a dish, its remaining contents are poured into a 3-liter beaker labelled "Sorted."
5. Each dish of sorted organisms is checked for final identification when its contents are enumerated and/or measured as noted in Table 2. Fish larvae are measured to the nearest one-half millimeter on a transparent millimeter rule (specifications below). Each measured species is tabulated on the form illustrated and described in Figure 26.

Note: The scale for measuring fish larvae is a transparent plastic rule, about 0.5 mm thick, on which the markings, in millimeters, are etched on the plastic. A piece of the rule, about 50 mm, is taped between two thin pieces of glass—usually standard microscope slides $76 \times 51 \times 1$ mm. The larvae are piled in a small mass on the slide,

and individual specimens are gently dragged over the top of the scale with a clean dissecting needle. After measuring, they are dragged away into another pile until all are measured. Finally they are placed in a vial and labelled.

6. The sorted plankton (invertebrates) is poured into the mesh cone to drain off the water, and the plankton is returned to its original jar and preservative. (When a cruise is completed the samples are sent to SIO for curation and study of selected invertebrates.)
7. When the checking in step 5 is done another form, the sorter's work sheet (Fig. 27), is filled out listing the numbers of organisms of each type sorted. The form also includes other information as illustrated. Whole larvae, head sections and tail sections are listed and totaled for all species measured and for other fish larvae. Totals listed for measured larvae should be the same as those on the tabulation sheets; (exceptions noted in caption for sorter's work sheet—Fig. 27) the totals of head and tail sections should equal the DIS on the tabulation sheets (Fig. 26).

Table 2.—Organisms identified and enumerated and/or measured during sorting of CalCOFI plankton samples.

Species	Common name	Labelled	Enumerated	Measured ¹	Scanned ²
<i>Sardinops caeruleus</i>	Pacific sardine eggs larvae	Sardine E L	X X	-- X	-- --
<i>Engraulis mordax</i>	Northern anchovy eggs larvae	Anchovy E L	X X	-- X	-- --
<i>Merluccius productus</i>	Pacific hake eggs larvae	Hake E L	-- X	-- X	-- ³ --
<i>Cololabis saira</i>	Pacific saury eggs larvae	Saury E L	X X	-- --	-- --
<i>Trachurus symmetricus</i>	Jack mackerel eggs larvae	Jack mackerel E L	-- ³ -- ³	-- -- ³	-- ³ -- ³
<i>Etrumeus acuminatus</i>	Round herring eggs larvae	<i>Etrumeus</i> E L	X X	-- --	-- --
	Other fish eggs larvae	OFE OFL	X X	-- --	-- --

¹ To nearest one-half millimeter.

² Categorized.

³ Occasionally.

- Each group of organisms is placed in a 2-dr vial with screw cap. An appropriately marked label is placed in each vial, and the vial is capped. Each label includes cruise number, station number, date of tow, organism name and total. If organisms were measured this is indicated on the top of the cap on a self-adhesive label. Labels are written with pencil (grade equal to "H") or waterproof ink (Higgins Engrossing Ink, No. 892, which does not clog the type of pen used here—Kohinoor Rapidograph, No. 0 or 00).

Note: Paper for labels should be 100% rag content. Inferior quality paper eventually deteriorates in Formalin or loses legibility.

The type of screw cap used here is plastic with a vinyl insert (Fig. 28) that is "self-sealing" when screwed tightly on the vial, thus preventing evaporation for long periods of time and decreasing amount of curating time needed to replenish evaporated preservative (see section on Curating). This is much preferred over corks, rubber stoppers, or screw caps with paper liners.

- All material is checked including the work sheets and vials with labels.
- A sorter's master sheet (Fig. 29) is compiled on which the sorting data are summarized for each station from each sorter's work sheet.

- The vials of each station are banded and arranged in numerical order of stations in small cardboard boxes for delivery to the identification group and further work.

Identification of Fish Eggs and Larvae

When the identifiers receive the vials and master sheets from the sorting laboratory their procedures are generally as follows:

- All eggs and larvae identified and enumerated by the sorters are verified, and their numbers listed in the appropriate boxes at the tops of the columns on the form illustrated in Figure 30. Since our primary interest is in certain commercial species, those are prelisted as shown on the form.
- The OFE's (see Table 2) are verified. If any of the form's prelisted species have been overlooked by the sorters, they are listed and added to the totals on the form shown in Figure 30. (Also see Figure 32 for method used for automatic data processing.)
- The OFL's (see Table 2) are identified according to the classifications of Berg and listed in the large space on the form. *Sebastes* = *Sebastes* (rockfishes)—not the responsibility of the sorters—if present, are totaled and listed in the appropriate box. Flatfishes, some of which are com-

1 of 2

SPECIES: Anchovy CRUISE: 6801 STATION: 80.52 R
 MEASURER: S. Vanden Bergh TOTAL LARVAE: (719) DIS: (3)

LENGTH (MM.)					TOTAL
2.0					1
2.5					1
3.0					4
3.5	<del> </del>				24
4.0	<del> </del> <del> </del> <del> </del> <del> </del>				61
4.5	<del> </del> <del> </del> <del> </del>				29
5.0	<del> </del> <del> </del> <del> </del>				38
5.5	<del> </del> <del> </del> <del> </del>				34
6.0	<del> </del> <del> </del>				30
6.5	<del> </del> <del> </del> <del> </del>				37
7.0	<del> </del> <del> </del> <del> </del> <del> </del>				69
7.5	<del> </del> <del> </del> <del> </del> <del> </del>				54
8.0	<del> </del> <del> </del> <del> </del> <del> </del>				64

Figure 26.—Plankton sorter's tabulation sheets for measuring fish larvae—sample copy of one of two sheets used to measure anchovy larvae for station 80.52, cruise 6801, regular mesh (505 μ). The tabulations are made up on two sheets to include lengths of larvae by 0.5-mm sizes from 2.0 to 8.0 and 8.5 to 15.0 m with additional lines for longer larvae. At the bottom of the second sheet is a line for tabulating disintegrated larvae (DIS).

mercial species, if present, are listed first on the form, then all other OFL's and myctophids. The methods of identification in the taxonomy of fish larvae, worked out by E. H. Ahlstrom of our laboratory, are too involved to be discussed here. Suffice to say that the larvae of at least 100 families are found in the California Current area. At present, approximately 100 kinds can be identified to species, 40 to genus and the rest to family. Size is an important factor in identification since identifying characters of larvae change with growth. The identifiers can recognize more than 1,000 sizes, shapes, pigment patterns, eye forms,

etc., which characterize individual larvae of the various species.

During identification the OFL's are checked for overlooked species that are the responsibility of the sorters. In most cases of omission, the larvae are in such poor state that it may be impossible for the sorters to have identified them or so poor a state that they could not be identified at all. If identifiable, they are added to the other totals, where appropriate; if not they are put into a disintegrated (DIS) category. All identified fish are returned to one vial. Some, if in excellent condition, may be kept out for further study or the reference file.

TOTAL ORIGINAL VOLUME 68 SAMPLE NUMBER 6801-H-80.52 REG.
TOTAL ORIG. VOL. MINUS LG. ORG. 68 DATE COLLECTED I-18-68
FRACTIONED: YES (NO) SORTING:
PERCENTAGE _____ RIGHT DATE STARTED: 6-18-68
_____ LEFT TIME STARTED: 1:30 PM
PERCENTAGE VOLUME _____ PERSON SORTING DK
REMARKS: (Such as overall condition, etc.) PREDOMINANT TYPES OF PLANKTON: _____
Condition #4 very dirty, thinning necessary because of organism variety to be identified Amphipods
Engelmann
Hydromedusae
Phyco. Red algae
SARDINE EGGS _____
SARDINE LARVAE _____
WHOLE _____
HEAD SECTIONS: _____ TAIL SECTIONS: _____
ANCHOVY EGGS: _____
715 ANCHOVY LARVAE: _____
WHOLE 712 _____
HEAD SECTIONS 3 TAIL SECTIONS 3
SAURY EGGS _____
SAURY LARVAE _____
ETRUMEUS EGGS _____
ETRUMEUS LARVAE _____
132 OTHER FISH EGGS _____
457 OTHER FISH LARVAE _____
WHOLE 457 _____
HEAD SECTIONS _____ TAIL SECTIONS _____

Figure 27.—Plankton sorter's work sheet—sample copy for station 80.52, cruise 6801-H, regular mesh (505 μ). Note that the count of anchovy larvae does not match that of the sorter's tabulation sheet in Figure 26. A sorter's count in such high numbers is rarely exact. The measurer's count is exact because every larva is tabulated as it is measured. The sorter's original count on the master sheet (Fig. 29) has been changed by the measurer.

4. If sardine eggs are in the sample they are staged according to the method devised by Ahlstrom (1950) as to their state of development in 11 phases from fertilization to full development before hatching. Then they are aged according to the water temperature and time of day at which they were collected.
5. All labels are the same as those for plankton sorting. If larvae are bottled separately,

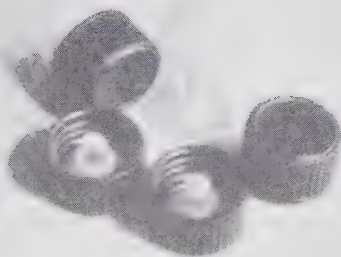


Figure 28.—Two-dram (7.4 ml) vials and caps used for sorted and identified fish eggs and larvae. Note vinyl insert in caps (see text).

6801

REG. Mesh

STATION	TOTAL Volume	T. V.— La. Res.	% of FACT + VOL	SARDINE ANCHORY		SAURY		SPERMUS		OTHER		Hake	
				F	LF	LE	LF	LE	LF	LE			
60.50	17	17								219	48	S.G.C.	7
52	30	30								1749	307	M.J.K.	5
55	44	44					1			28	138	S.G.C.	36
60	131	131								263	55	S.G.C.	6
70	339	339								131	130	R.M.	1
80	125	125								126	98	S.G.C.	0
90	43	43								18	35	M.J.K.	1
100	21	21								12	4	M.J.K.	
63.50	12	12								516	1078	P.A.	
52	40	40					1			344	638	M.J.K.	22
55	66	66					5			65	1376	S.G.C.	61
60	104	104								51	102	S.V.	11
70	201	201								77	87	S.V.	1
80	244	244								132	47	P.A.	1
90	67	67								7	6	M.J.K.	1
67.48	23	23				334	19			1039	116	M.J.K.	1
50	69	69								42	434	P.A.	6
55	163	163					24			42	529	S.G.C.	55
60	95	95								108	119	S.V.	8
70	67	67								112	195	S.V.	0
70.51	1815	975					7			25	181	S.G.C.	41
53	93	93					2			73	228	S.V.	50
60	152	152								61	34	M.J.K.	9
70	71	71								92	306	S.V.	279
80	61	61								7	56	P.A.	0
90	86	86								9	8	S.G.C.	0
100	47	47								14	23	S.V.	2
73.50	48	48								89	756	S.V.	55
53	74	74								136	334	M.J.K.	52
60	112	112								33	77	P.A.	10
70	63	63								49	24	S.G.C.	0
100	28	28								9	15	P.A.	6
77.48	41	41				1	20			865	315	R.M.	1
51	74	74					2823			38	1072	P.A.	77
55	59	59					4			341	3404	M.J.K.	3232
60	110	110					1			282	72	P.A.	17
100	23	23								3	334	R.M.	1
80.51	66	66								110	501	P.A.	17
52	68	68								132	457	M.J.K.	27
55	95	95								302	316	R.M.	149
60	83	83								779	4651	M.J.K.	3641
65	71	71					22			19	2874	P.A.	226
70	58	58					10			30	125	P.A.	21
80	100	100								5	18	P.A.	
90	64	64								2	31	P.A.	
100	334	334								9	29	R.M.	
82.47	55	55								1041	205	M.J.K.	27
83.40	19	19								4339	43	S.V.	74
43	24	24								1044	214	S.G.C.	2341
51	43	43								134	388	S.V.	24

Figure 29.—Plankton sorter's master sheet—sample copy for stations 60.50 to 83.51, cruise 6801. Numbers of hake larvae are out of order (last column is usually that of sorters' initials) because hake counts were made after this cruise was completed. (See note for Figure 27, indicating reasons for changes in numbers of anchovy larvae.)

from the rest of the sample, this fact is noted on the enumeration sheet and on the back of the label in the vial in which they would have normally been placed. Vials are stored by numerical order of cruise and cruise station in specially constructed cardboard boxes $3 \times 5 \times 7\frac{1}{2}$ inches with lids, each containing 60 vials labelled appropriately on the outside of the box by category and cruise. Each cruise may have from 10 to 28 boxes depending on the abundance of organisms and time of year of a survey.

The boxes are stored by cruise in a special area in the laboratory.

REFERENCE COLLECTION

A special reference collection, the "larva library", is kept adjacent to the identification laboratory. The specimens in this collection are usually the "best of a kind" and used for reference in identifying questionable material or rare specimens whose characteristics may have been forgotten over long periods of time. The material is also used occasionally to train identifiers.

Cruise 6801Station 80.52 RegSHF 2.78Total Larvae 1175

Anchovy L.	Sardine L.	J. mackerel	Pac. mackerel	Hake	Sebastodes	Anchovy E.	Sardine E.	Saury E.
719				29	326			
1,998.8				80.6	(S. paucispinus - 2) (S. jordani - 13) 906.3 Citharichthys sp - 17 - 47.3 (C. stigmaeus - 1) (C. sordidus - 2) Goby - 5 - 13.9 Protomyxodophus - 3 - 8.3 Leucoglossus - 12 - 50.0 S. leucopsaurus - 45 - 125.1 Palometa - 1 - 2.8 Tautoglabrus - 1 - 2.8 Sciaenids - 10 - 27.8 Scorpaenichthys - 1 - 2.8			
Std. Total 3,266.5								

Figure 30.—Identifier's tabulation sheet (see text for description of form)—sample copy of sheet for station 80.52, cruise 6801 (compare with plankton sorter's tabulation sheet and work sheet for the same station, Figures 26 and 27). On this form, the whole numbers are the identifier's counts for all species; their total is in the upper right hand corner. No change is made on the sorter's master sheet (Fig. 29). Standardized numbers (the decimals) are obtained by multiplying each species number by the standard haul factor (SHF—top line—obtained by standardization of data; see text and Figure 37) and adding them for the standard total at bottom right of largest space. Procedures used in automatic data processing of these identified species are described in the text and illustrated in part in Figures 31 and 32.

CURATING

The general and reference collections are periodically checked to assess the evaporation of preservative from the vials. The screw-top lid with the vinyl liner (Fig. 28, also see section on Plankton Sorting) now used on our vials is virtually evaporation-proof if well tightened when stored. Occasionally some vials with loose caps may lose liquid by evaporation in which case preservative is added, the cap tightened properly, and the vial stored again.

Standardization

During tows for plankton, different volumes of water are strained through the net depending on different speeds of the tow (more water with high speed) or different times of tow (in shallow versus standard depths).

In order to make tows comparable, all hauls are adjusted to a standard amount of water strained per unit of depth fished—10 m³ of water strained per meter of depth fished. This value is used because it gives a factor of approximately

Figure 31.—Sample sheet of code numbers, for automatic data processing, assigned to the fishes of the California Current region. Coding was made on the basis of phylogenetic sequence of orders, families, genera and species, and some common names. Some numbers were left out in sequences to allow for insertion of new finds or possible name changes, some of which are illustrated here. The list was converted to alphabetical order to make it easier for statistical personnel, unfamiliar with phylogenetic sequence, to find and use the proper numbers when assigning them to the identifiers' sheet (see Fig. 32).

641	Pimelometopon pulchrum	560	"Scombrid"
791	"pipefish"	560	Scombridae
949	<i>Phylloniscus stelleri</i>	560	"Scombroide"
940	Pleuronectidae	335	Scopelarchidae
951	Pleuronichthys coenosus	336	^{Nes} Scopelarchoides dentatus
952	Pleuronichthys decurrens	338	Scopelarchus
953	Pleuronichthys ritteri	409	Scopeloberyx robustus
954	Pleuronichthys sp.	409	"Scopeloberyx nycterinus"
955	Pleuronichthys verticalis	412	Scopelogadus mizolepis bispinosus
490	Polynemidae	412	"Scopelogadus bispinosus"
625	Pomacentridae	196	Scopelosaurus
600	Pomadasyidae	678	Scorpaena guttata
531	Pompano	736	Scorpaenichthys
821	Porichthys	670	Scorpaenidae
404	Poromitra	665	Scorpidae
756	Prionotus	683	Sebastodes spp.
288	Protomyctophum crockeri	707	Sebastolobus
189	<i>Protomyctophum</i> sp.	516	Seriola
523	Psenes	425	Serranidae
958	Psettichthys melanostictus	641	Sheepshead
420	"puffer"	605	<i>Sphyrna tiburo</i>
670	"rockfish-not sebastodes"	486	Sphyrna argenta
855	"ronquill"	485	Sphyrnaeidae
571	Sarda	835	"stargazer"
019	"sardine"	292	Stenobranchius leucopsarus
019	Sardinops caerulea	100	Sternoptychidae
020	<i>Sardinops sagax</i>	107	Sternoptyx
166	"saury"	121	Stomias
650	Scaridae	120	Stomiidae
610	Sciaenidae	109	<i>Stomatopoda</i>
165	Scomberesocidae	530	Stromateldae
574	Scomber japonicus	310	"Sudid"
577	Scomberomorus		

1.0 for a net with a 1.0-m-diameter mouth opening. A standard haul factor (standardization factor) is derived for each haul by the following formulation:

$$S = \frac{10 D}{V} \text{ or } \frac{10 D}{R a p}$$

where S = standardized haul factor (= SHF).
 D = average depth of haul—derived by multiplying the cosine of the average angle of stray by the length, in meters, of the towing cable. (The cosine of the average angle of spray, derived from a tangent of all angles, is considered more representative of the haul as a whole than the cosine

of the angle of stray at the greatest depth.)

V = total volume of water strained in cubic meters.

R = total number of revolutions of the current meter during the tow.

a = cross section area of mouth of net in m.²

p = length of the column of water, in meters, needed to effect one revolution of the current meter at average speed at which the haul was taken (determined from the appropriate calibration graph—see calibration of flowmeters).

Anchovy L.	Sardine L.	J. mackerel	Pac. mackerel	Hake	Sebastes	Anchovy E.	Sardine E.	Saury E.
(719)				(29)	(326)			
031				901	(S. paucispinus - (20))		683	
					(S. jordani - (3))			
					Citharichthys sp. - (17)		924	
					C. stigmatus - (1)			
					(C. sordidus - 2)			
					Goby - (5)		795	
					Leuroglossus - (18)		072	
					Palometa - (1)		531	
					Suidanids - (2)		610	
					Scorpaenids - (1)		736	
					Protomyxophorus - (3)		289	
					S. leucopsarus - (45)		292	
					Turriculobea - (1)		299	

Figure 32.—Identifier's tabulation sheet with the same identifications as those listed in Figure 30. Here, however, code numbers for the identifications (see Fig. 31) have been written in for keypunching and automatic data processing.

CALIBRATION OF FLOWMETERS

For calibration, a meter (s) is hauled or pushed at different speeds over a measured distance. (Our personnel have developed a method for calibrating three meters at a time, fastening them to a bracket under a board—Figs. 33 and 34—and pushing them over the measured distance—42 ft = 12.2 m.) Performance tests are made before (Fig. 35) and after every cruise, and a graph is constructed in which the independent variable is the length of a column of water needed to affect one revolution of the meter (meters per revolution) at any given towing speed. The graph (Fig. 36) applicable to a given cruise is based on the average of two calibration trials. The graph is curvilinear with the highest values of m/rev associated with the lowest numbers of

rev/sec because of friction at low speeds. The curve flattens out with increase in speed and a corresponding decrease in friction.

With preparation by automatic data processing (ADP), the meter calibrations are key punched and programmed to produce a regression line where meters per revolution are plotted against seconds per revolution in order to linearize the relationship over the range of values obtained in all the plankton tows for which the meter was used.

Standardization of data for every station on a cruise is begun with the preparation of four "sets" (Fig. 37) as follows:

Set I — to derive the SHF from the for-

$$\text{mula } S = \frac{10 D}{V} = \frac{10 D}{R a p}$$

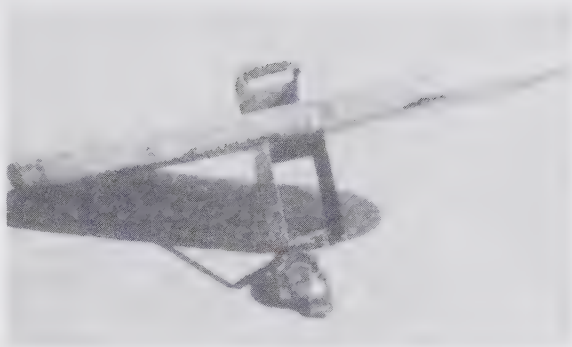


Figure 33.—Board used to calibrate T.S.-Flowmeters (one meter attached). The board is balsa wood, covered with fiber glass to make it waterproof, 4 ft long, 15 inches wide $\times$ 2-1/2 inches thick (151.9 $\times$ 38 $\times$ 6.4 cm).

- Set II — to determine the volume of plankton collected per 1,000 m³ of water strained.
- Set III — the station data and plankton volumes for publication.
- Set IV — to adjust SHF to percent of sample sorted—no longer done—see note following description of Set IV below.

In addition, if an improper meter reading was obtained or was missing for any tow, a scatter diagram and regression line (Fig. 38) had to be plotted and calculated for all meter readings (ordinate) against all average tangents (abscissa) in order to obtain an estimate of a meter "reading" to apply to that tow (see parenthesized data for station 60.70 in Figure 37).

Each set duplicated the cruise number, the ship, the dates of the cruise—start to end, meter number(s) and net number(s).

On Set I, 14 columns are used of which the last is the SHF. The column headings are as follows:

1. Station number—from tow data sheet.
2. Order occupied—from tow data sheet.
3. Total time of tow in minutes and seconds—from tow data sheet.
4. Total time in seconds—derived from 3.
5. Current meter revolutions, difference in final and initial reading—from tow data sheet.
6. Revolutions per second current meter, from 5, divided by time in seconds.

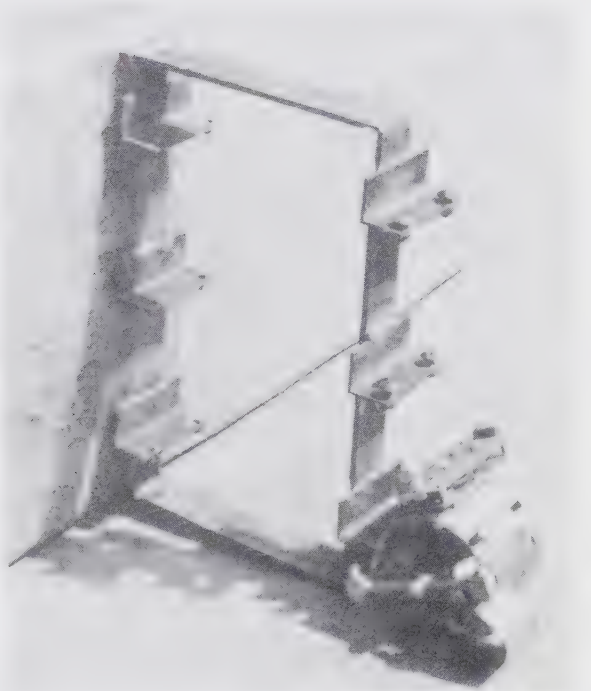


Figure 34.—Brass frame under calibration board (see Fig. 33) on which to hang flowmeters. Only three meters are calibrated at one time, the hangers nearest the board are not used; meter readings were found to be erratic because of the turbulence in that area. The brass frame is 8 inches $\times$ 14 inches (20.3 $\times$ 35.5 cm) made of four pieces of brass welded at their ends. The brass material is 3/16 inch $\times$ 2 inches (5 $\times$ 51 mm). The brass angles on which to hang the meters are cut from 1/8-inch (3 mm) stock, 1-1/4 inches (32 mm) each side, 3 inches (72 mm) long. Holes are bored to conform to distance on centers of holes in meter lugs. Nuts are welded in position to take bolts that slip fit through meter lugs. Meters just hang on the bolts.

7. Average tangent—derived from tangents of all angles taken during tow.
8. Calibration factor = meters per revolution, the p in formula above—taken from calibration curve (Fig. 36).
9. Calibration factor $\times$ areal cross section of net = a constant which, when multiplied by R (total revolutions/haul) gives
10. Volume of water strained = Col 5 $\times$ Col 9
11. Cosine of average tangent from Col 7
12. Wire out = total wire out before net is hauled in
13. STD haul factor =
$$\frac{\text{Col 13} \times 10}{\text{Col 10}}$$

CURRENT Meter - # 1179

$$40' \text{ ft.} = 12.2 \text{ m}$$

Calib.
6/21/66
Hydraulics Lab
By LWF

Secs.	Revs	Rev/ Sec	M/ Rev.
14.2	105	7.39	.145
16.7	106	6.35	.144
18.8	105	5.59	.145
19.7	107	5.43	.142
21.7	106	4.88	.144
23.5	105	4.47	.145
25.8	107	4.15	.142
28.4	103	3.63	.148
29.4	105	3.57	.145
31.8	104	3.27	.147
34.0	103	3.03	.148
35.5	106	2.99	.144
38.0	104	2.74	.147

Figure 35.—Calibration of flowmeter—sample copy of record for meter #1179 on June 21, 1966. The meter, with others on a board (see Fig. 33 and 34), is pushed over a measured distance at a number of speeds, in this instance 13 runs at approximately 15 to 40 sec. The meters per revolution are plotted against revolutions per second for part of the calibration curve shown in Figure 36.

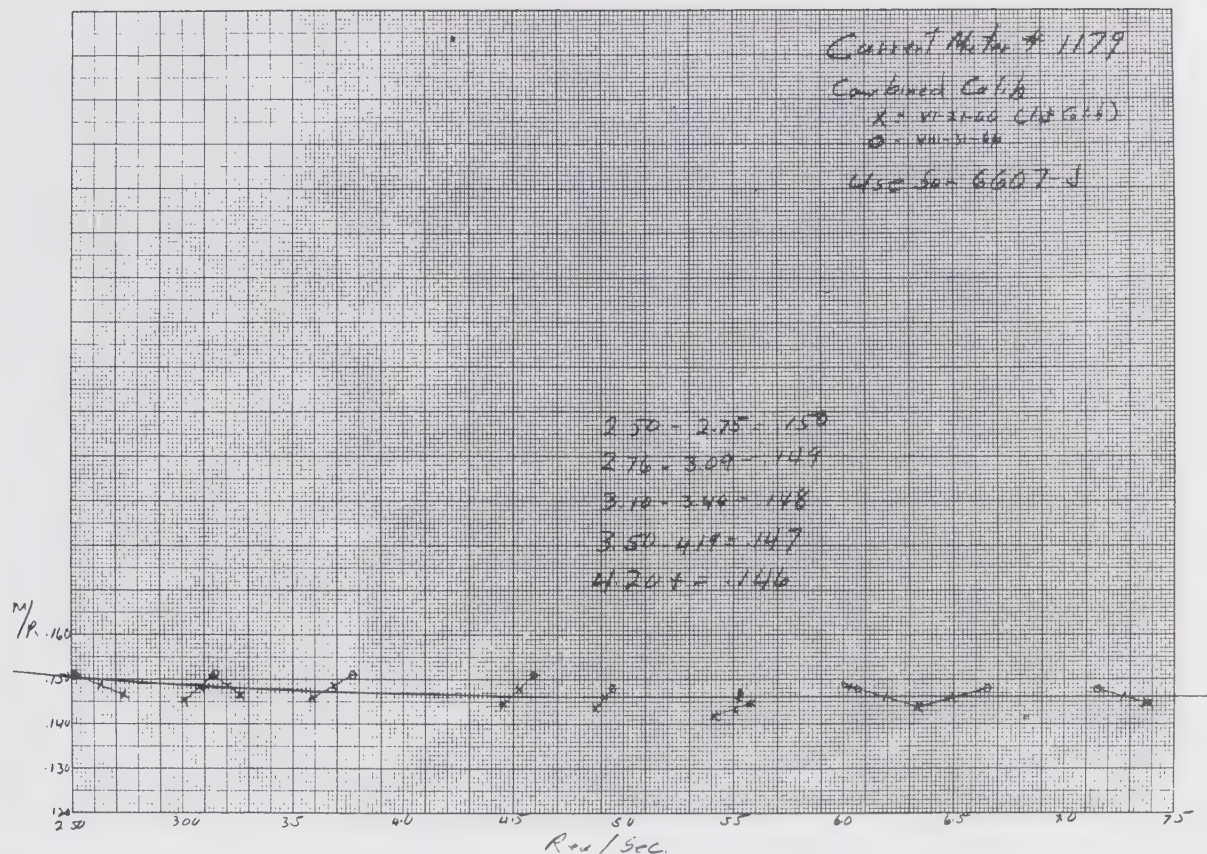


Figure 36.—Calibration curve for flowmeter #1179 obtained by plotting two sets of calibrations and drawing the curve on the average of the calibration points. The data of the first calibration are shown in Figure 35, the second, a similar set, made after cruise 6607-J are not illustrated.

Set II derives the plankton volume per 1,000 m³ water strained by the following formula:

$$V_{p/m^3} = \frac{V_p}{V_w} 1,000$$

where V_{p/m^3} = plankton volume per 1,000 m³ water strained.

V_p = plankton volume collected in net tow (from plankton measured).

V_w = cubic meters of water strained (from Set I).

Set III combines all the station data for publication.

Set IV adjusting for percent plankton sorted multiplies the SHF by reciprocal of the fraction sorted, e.g., 50% (one-half) of sample, multiply SHF by 2, 25% (one-fourth) sorted, multiply SHF by 4, etc.

Note: It has often been found that when some organism such as rare and/or larger fish larvae are scarce, fractioning a sample tends to give an erroneous count of actual numbers present, where it is highly probable that the few specimens in a sample can be left in the unsorted portion of the plankton. Therefore, it has been our policy of late to sort 100% of all samples.

With automatic data processing only two sets are printed out, one to obtain volumes of water strained, the standard haul factor for each plankton haul as for Set I above, and the other to produce station data and plankton volumes as for Set III above.

These data sheets are prepared by using 20 items from plankton tow sheet (circled numbers on the tow sheet), the plankton volumes and the data of the computer's calibration curve described above.

For the new Set I, a printout will include stations indicating errors or omissions of meter

SET I
1 OF 3

CRUISE NUMBER : 6607-J
VESSEL : Jordan
DATES : VII-9/28-66
CURRENT METERS : 1179, 1181
MESH SIZE : 30XX 51K

	STATION	ORDER OCCUR	TOWING TIME MIN	TOWING TIME IN SEC	REV OF CURRENT METER	REV / SEC	AVERAGE TANGENT	CALIB FACT	7854 C.F. X CONST	VOL H ₂ O STR (M ³)	COSINE OF AV. TAN.	WIRE OUT (METERS)	DEPTH OF TOW (METERS)	STAND. HAUL FACTOR
1	60.50	1	4 00	240	1000	4.17	1.424	1.47	11545	115.4	.572	60	34.3	2.97
2	60.52	2	7 31	451	1982	4.39	1.046	1.46	11467	227.3	.691	100	69.1	3.04
3	60.55	3	11 45	705	3032	4.30	1.071	1.46	11467	347.7	.682	160	169.1	3.14
4	60.60	4	14 34	874	3817	4.37	1.027	1.46	11467	437.7	.678	200	199.6	3.19
5	60.70	5	14 32	872	(3436)	(4.17)	1.102	1.47	11545	(419.8)	.572		134.4	(3.20)
6	60.80	6	14 47	882	3564	4.04	1.125	1.47		411.5	.564		132.8	3.23
7	60.90	7	14 40	850	3256	3.81	1.025	1.47		387.4	.572	200	139.6	3.60
8	63.50	8	3 11	197	720	3.65	1.195	1.47		85.1	.571	40	25.6	3.08
9	63.52	9	7 43	463	1942	4.19	1.013	1.47		224.2	.703	100	76.3	3.14
10	63.55	10	14 37	877	3268	3.73	.992	1.47	11545	377.3	.710	200	142.6	3.76

SET II
1 OF 3

CRUISE NUMBER : 6607-J
VESSEL : JORDAN
DATES : VII-9/28-66
MESH SIZE : 30XX 51K (Reg.)

	STATION	VOL. H ₂ O STR. (M ³)	DISPLACEMENT VOL. OF PLANKTON TAKEN IN TOW TOTAL (ML)	SM. ORG. (ML)	PLANKTON VOLUME PER 1000 M ³ OF H ₂ O STR. TOTAL (ML)	SM. ORG. (ML)
1	60.50	115.4	51		442	
2	52	227.3	266	66	1170	290
3	55	347.7	183		526	
4	60	437.7	192		439	
5	70	(419.8)	409		(974)	
6	80	411.5	182		412	
7	90	387.4	427		1102	
8	63.50	85.1	6		72	
9	52	224.2	69		308	
10	65	377.3	643		1704	

SET III
1 OF 3

CRUISE NUMBER : 6607-J
VESSEL (S) : Jordan
DATES : VII-9/28-66
MESH SIZE : 30XX 51K

	STATION	POSITION N. LAT. W. LONG.	DATE 19 66	TIME (P.S.T.) START END	VOL H ₂ O STR. (M ³)	DEPTH OF TOW (METERS)	PLANKTON VOLUME PER 1000 M ³ OF H ₂ O STR. TOTAL (ML) SM. ORG. (ML)
1	60.50	37 57.5 122 52.5	VII - 9	1404 1408	118	0-34	442
2	52	37 54 123 01.1	- 9	1458 1505	227.3	0-69	1170 290
3	55	37 47 123 15	- 9	1647 1659	348	0-109	526
4	60	37 37 123 37	- 9	1816 1921	438	0-140	439
5	70	37 17 124 21	- 10	0001 0016	(420)	0-134	(974)
6	80	36 56.5 125 04	- 10	0456 0511	412	0-132	412
7	90	36 37 125 47	- 10	1016 1020	387	0-140	1102
8	63.50	37 23.3 122 27.8	VII - 11	1529 1533	85	0-26	72
9	52	37 14 122 36	- 11	1403 1411	224	0-80	308
10	55	37 13 122 50	- 11	1436 1444	377	0-142	1704

SET IV
1 OF 3

CRUISE NUMBER : 6607-J
VESSEL (S) : Jordan
DATES : JULY-28, 1966
MESH SIZE : 30XX 51K

	STATION	DATE 19 66	MID-TIME OF TOW (P.S.T.)	STAND. HAUL FACTOR	PERCENT SORTED	S.H.F. CORRECTED TO % SORTED
1	60.50	VII - 9	1407			
2	52	- 9	1505	2.97		
3	55	- 9	1654	3.04		
4	60	- 9	1925	3.14		
5	70	- 10	0010	3.19		
6	80	- 10	0505	(3.20)		
7	90	- 10	1025	3.23		
8	63.50	VII - 11	1531	3.60		
9	52	- 11	1408	3.08		
10	55	- 11	1438	3.14		
			1135	3.76		

Figure 37.—Sample copies of standardization of data in sets for the first 10 stations of cruise 6607-J (see text for methods).

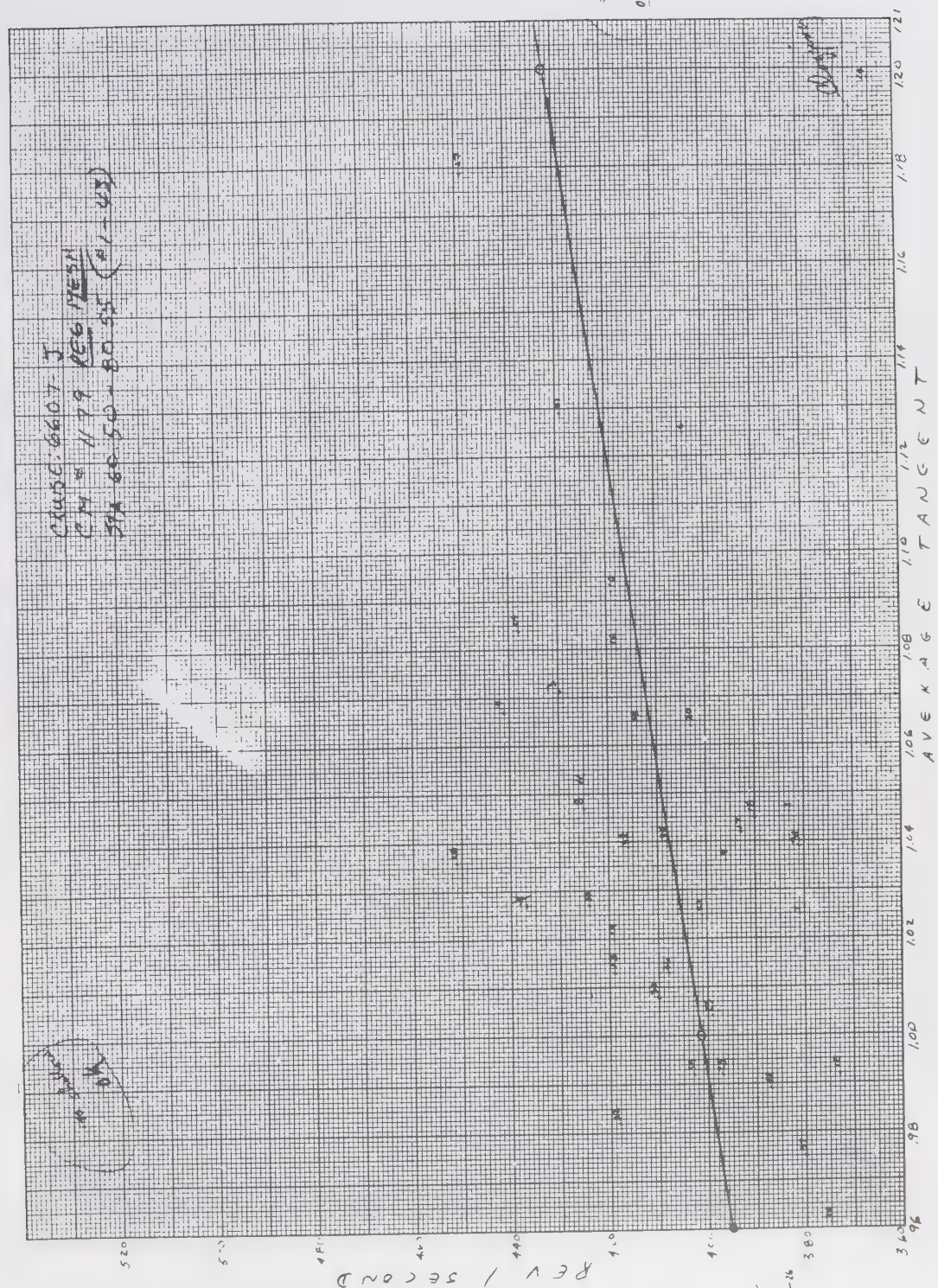


Figure 38.—Regression line derived from data of stations 60.50 to 80.55, Nos. 1 to 43 by order of occupancy on cruise 6607-J. The line was needed to obtain an estimated meter reading for station 60.70 on which a sample was collected and a proper set of wire angles recorded, but the tow was not repeated. When the line was drawn, the "reading", 4.17 rev/sec, was obtained by taking the point off the line at the average tangent 1.102. All data derived from such an estimate are parenthesized in the data sets in Figure 37.

readings if any. A scatter diagram with regression data are printed out and a second and final Set I is printed with corrections showing estimated meter readings, volumes of water strained, and the SHF derived from them.

Note: A scatter diagram and regression data are prepared whether needed or not in order to present a visual record of meter behavior during a cruise.

The final step in standardizing the data is to multiply all counts of eggs and larvae from each plankton tow by the standardized haul factor (Fig. 30). The standardized counts are filed on species cards by cruise and station. Measured larvae are standardized by numbers per size to the nearest one-half millimeter, then grouped in size classes, e.g., Kramer (1971). Sardine eggs are standardized by stage of development and totaled in "Age in Days" (see Step IV in identification of eggs and larvae), e.g., Kramer (1971).

For ADP a coding system is used now to standardize the data. A number (code) is assigned to each fish larva, sized or unsized, as far as possible to order, family, genus or species (Fig. 31). The code numbers are added to the identifiers sheet as shown in Figure 32, and the key punch operator puts the following information on a card for each species: cruise number, station number, larva or egg code number, and the standard haul factor.

These data are then stored on tape for retrieval for analysis and/or publication.

Data Publication

The data for each year of surveys are compiled for publication in two series. The first is "Zooplankton volumes of the Pacific coast, . . .," the old Sets III (now Set II by ADP) for each survey, e.g., Thrailkill (1969). The second is "Sardine eggs and larvae and other fish larvae of the Pacific coast, . . .," which include the stand-

ardized haul factors for all stations occupied on each survey and positive occurrences of particular species as follows: Pacific sardine eggs by age in days, fish larvae by size classes including Pacific sardine, northern anchovy, jack mackerel and Pacific mackerel, and fish larvae unsized, including Pacific hake and rockfish spp., e.g., Kramer (1971).

ACKNOWLEDGMENTS

Sincere appreciation is extended to all personnel and organizations without whose cooperation the exacting procedures and extensive work of the CalCOFI could never be accomplished.

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THE RESPONSE OF SALTON SEA FISH EGGS AND LARVAE TO SALINITY STRESS¹

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In laboratory experiments, Salton Sea water at salinities (S) of 40 ‰ and higher adversely affected developing embryos and larvae of the croaker, *Bairdiella icistia*, and the sargo, *Anisotremus davidsoni*. Embryos developed abnormally, hatching success diminished, and mortality of larvae was greater than in normal Salton Sea water at 37.6 ‰ S.

INTRODUCTION

The Salton Sea is an inland saline lake, 58 km long and 14.5 to 24 km wide, in the desert of southeast California. Originally formed in 1905-1907 by accidental diversion of flood water from the Colorado River, the Salton Sea has since been maintained by agricultural drainage from surrounding land. A few species of marine fish were introduced into the sea as long ago as 1929 when the Sea was about 14.5‰, but most successful introductions were made from 1948 through 1956 at higher salinities. Carpelan (1961) gives an excellent review of the physical and chemical history of the Sea. The sport fishery in the Salton Sea presently depends on three introduced species from the Gulf of California, the bairdiella, *Bairdiella icistia*, the sargo, *Anisotremus davidsoni*, and the orangemouth corvina, *Cynoscion xanthulus*. The bairdiella supports only a minor sport fishery and is primarily a forage fish for the highly prized corvina; both of these species belong to the croaker family, Sciaenidae. The sargo, of the family Pomadasyidae, is both an important game fish and a forage fish (Walker, Whitney, and Barlow, 1961). Because of a persistent increase in the salinity of the Salton Sea in recent years due to agricultural soil leaching (Federal-State Reconnaissance Report, 1969), concern has been expressed for the continued survival of these three species on a self-sustaining basis in the Salton Sea (Calhoun, 1969).

The ability to survive stresses in the environment is generally less developed in early larval stages as evidenced by the huge mortalities which occur at this time. There is ample evidence that the greatest degree of mortality occurs in fishes during the egg and larval stage of development, (Sette, 1943; Ahlstrom, 1954). Pelagic fish larvae often

¹This work was performed as part of Dingell-Johnson Project, California F-24-R, "Salton Sea Study," supported by Federal Aid to Fish Restoration Funds. Accepted for publication September 1971.

hatch from the egg before having fully developed the organs to see, feed, or osmoregulate. Development to the feeding stage proceeds with yolk providing the energy needed. In particular the newly-hatched pelagic larvae of *bairdiella* and sargo lack gills, an open gut, scales, and a functional kidney, all part of the adult's final organ complement for osmoregulation. Because of these facts it seemed appropriate to study the effects of increased salinity on the eggs and larvae of Salton Sea fish. Observations are reported here which were made on the fertilization success, development, hatching and survival time of *bairdiella* and sargo eggs and larvae as they were affected by high salinities. The results are discussed with respect to the steadily increasing salinity of the Salton Sea.

METHODS

When this study was initiated in 1968, no method was available for maturing and inducing spawning of Salton Sea fish in the laboratory. Thus mature sargo and *bairdiella* had to be caught by a trawl or gill net during their spawning season (April and July 1968 respectively), then stripped and the eggs fertilized aboard a motor launch. The developing eggs were brought back to the laboratory operated by California Department of Fish and Game at Salton City, where temperature was maintained at 17 C in an air-conditioned room; there was no temperature control aboard the launch where temperatures varied between 24.5 and 27 C. In 1970, Haydock (1971) perfected a method for inducing maturation and spawning of *bairdiella* under laboratory conditions. This simplified the salinity study by providing viable eggs and sperm for laboratory experimentation and permitted a rigorous temperature control unobtainable during the earlier experiments. The work performed in 1968 was therefore repeated in 1970 to determine whether the earlier lack of temperature control altered the response of *bairdiella* eggs and larvae to salinity stress sufficiently to vitiate the earlier conclusions. The results from both years were comparable. For the sake of completeness both series of experiments are described in detail here.

Obtaining Ripe *Bairdiella* and Sargo

Ripe *bairdiella* females were taken in the Salton Sea on May 20, 29, June 10, 12, 19, and 24, 1968, by trawl between 1830 and 2130, 0.4 to 1.6 km from the western shore between Salton Bay Marina and Salton City Keys. Despite the fact that more fish were examined between 0800 and 1700 than in the evening hours, not one was ripe during daytime. Although no fish were caught after 2130 it is probable that spawning continues into the night. Whitney (1961) found that the *bairdiella* has a diurnal pattern of spawning, with most early cleavage eggs appearing in the plankton during early evening. One ripe sargo was caught in a gill net at 0930, April 23, 1968, and the fact that it was still alive indicated that it was in the net a short time, probably less than 3 hr. Only one running-ripe male *bairdiella* was caught by trawl, but sperm obtained from other mature males proved capable of fertilizing ripe eggs. The sargo fertilization was accomplished using sperm also from a mature but not running-ripe male. In the 1968 series of experiments, fertilization for both species was carried out on shipboard.

Bairdiella of the 1969 year class were maintained in large tanks at the Fishery-Oceanography Center of the National Marine Fisheries Service, La Jolla, California, for approximately 7 months prior to fertilization experiments in 1970. These fish were subjected to a photoperiod, water temperature and feeding regime conducive to accelerated growth and maturation of the gonads (Haydock, 1971). In mid-March 1970, approximately 2 months in advance of the peak spawning period for this species in the Salton Sea, viable sex products were obtained. Running-ripe females were obtained by injections of gonadotropic hormones as described by Haydock (1971). Males were running-ripe without hormone treatment. Sargo, which were captured at the Sea prior to the spawning season, were acclimatized to laboratory conditions for only 6 weeks and only one female ovulated after hormone treatment.

Artificial Fertilization

The shipboard and laboratory fertilizations were carried out in the same way. Eggs were expressed from ripe females by gentle hand pressure on the abdomen and collected on a stainless steel lab scoop. Eggs were then separated and distributed as evenly as possible in a glass Petri dish and apportioned into 10 cm diameter finger bowls, each containing 50 ml of water at an appropriate salinity.

Milt expressed from a male was drawn into a bulb-operated pipette and introduced into each bowl containing eggs. The seminal mass was repeatedly drawn into the pipette along with some of the water in the test bowl and forcefully expelled among the eggs to insure adequate mixing of the gametes. In 1970, all fertilizations were performed at 21 ± 0.5 C.

The fertilized eggs of the bairdiella and sargo are slightly buoyant and float against the surface film if undisturbed, while most unfertilized eggs remain on the bottom of the dish.

Selection of bairdiella and sargo fertilized eggs for further observation and estimates of fertilization success were made on the basis of a sink or float criterion only in test salinities (S) of 37‰ or higher. At lower salinities we observed initial cleavage stages under low-power magnification (7 to 15 $\times$), 1 to 2 hr after fertilization. In 1968, Salton Sea water evaporated to a salinity of 71.8‰ was filtered through a membrane filter (pore size 0.45 μ) and diluted with demineralized water to desired salinities. In 1970, undiluted Salton Sea water at 37.6‰ was filtered through activated charcoal to remove dissolved organic substances and a membrane filter, 0.45 μ pore size, to remove particulates. Higher salinities to 55‰ were obtained by mild heat and prolonged evaporation after filtration. Analysis for specific ions and total dissolved solids were made on Salton Sea water and 2 $\times$ Salton Sea water in 1967. When compared with an analysis of sea water, these data show that some precipitation of calcium and sulfate must have occurred (Table 1).

Streptomycin sulfate assayed at 750 mg/g and penicillin-G, 1,585 units/mg, were added as dry powder (50 ppm) to some experimental vessels in 1968 and survival of eggs and larvae was compared with those without antibiotics. In 1970, only penicillin-G was used.

Usually 50 to 100 successfully fertilized eggs in a particular salinity were used for determining mortality rate. Dead eggs or larvae were removed whenever a count was made of living animals.

TABLE 1—Analysis of the Ionic Content of Normal Sea Water, Salton Sea Water, and 2X Salton Sea Water

	Sea water* (parts per thousand)	Straight Salton Sea water† (parts per thousand)	2X Salton Sea water† (parts per thousand)
Cations			
Ca.....	0.41	0.96	0.92
Mg.....	1.27	0.86	1.68
Na.....	10.6	11.5	22.5
K.....	0.38	0.22	0.37
Anions			
CO ₃	0.07	0.02	0.05
HCO ₃	0.14	0.15	0.27
SO ₄	2.65	7.0	12.0
Cl.....	19.98	17.8	35.5
Total dissolved solids.....	34.5	38.2	69.6

* Sverdrup, Johnson and Fleming (1946).

† Analyses by E. S. Babcock and Sons, Riverside, California.

RESULTS

Fertilization and Hatching Success

Successful fertilization of more than half of extruded eggs occurred at all salinities tested but there was a tendency toward lower success in the higher salinities. Usually, at least 50% of the eggs expressed from a sargo or bairdiella female could be fertilized regardless of salinity up to 55‰. In 1968, no eggs of bairdiella developed in 50 or 55‰ beyond blastodisc formation. Hormone-induced ovulation produced fertilizable eggs which occasionally survived to an advanced embryonic stage at 50‰ but always produced embryos which exhibited deformed tails and did not hatch. Fertilization success for sargo eggs was almost 100% at all salinities from 35 to 55‰.

Survival

Embryos of sargo and bairdiella in 45 and 50‰ Salton Sea water developed more slowly than those in lower salinities and hatching success diminished with increasing salinity. For example, in an experiment with bairdiella eggs in water containing antibiotics, hatching success was 84% in 35‰, 15% in 40‰, 7% in 45‰, and 0% in 50 and 55‰, although some eggs developed to late embryonic stages in the last two salinities.

In the experiment described in Table 2 which was performed in 1968 at 17 C, high salinities reduced the survival of *bairdiella* eggs and larvae. All eggs in the elevated salinities were treated with 50 ppm each of streptomycin sulfate and penicillin-G; however, there were no antibiotics in the 35‰ S Salton Sea water. Forty percent of the eggs survived to the yolk-sac larval stage even in the untreated 35‰ Salton Sea water 35 hr after fertilization and 78% survived in 33.5‰ La Jolla sea water, while in each higher salinity complete mortality occurred before 35 hr had elapsed, despite the addition of antibiotics. This effect was clear even in the 40‰ S experiment.

TABLE 2—Percent Survival of *Bairdiella icistia* Eggs and Larvae at Different Salinities. (Fifty eggs were fertilized in each salinity ($n = 50$ fertilized eggs = 100%) and observed over 35 hours at 17 C. Antibiotics, 50 ppm each of Streptomycin sulfate and penicillin-G, were added at the beginning of the experiment except in Salton Sea water of 35 ‰ S. Ripe *bairdiella* were caught by trawling. Stages of development are described in Mansueti and Hardy, 1967.)

Time from fertilization (hr)	Stage of development	Salinity (parts per thousand)					
		La Jolla	Salton Sea				
		33.5	35	40	45	50	55
0	Fertilized eggs.....	100	100	100	100	100	100
9	Early embryo.....	88	94	58	37	0	0
14	Early embryo.....	88	64	44	10	--	--
21	Yolk sac larvae.....	82	58	30	0	--	--
35	Yolk sac larvae.....	78	40	0	--	--	--

Antibiotics have a beneficial effect on survival. Salton Sea water at 35‰ was treated with antibiotics and the resultant mortality of *bairdiella* eggs and larvae measured over time. All the larvae were dead by 46 hr after fertilization when no antibiotics were used. In treated water 62% were alive after 46 hr, and 36% were still living and developing after 60 hr (Table 3).

TABLE 3—Percent Survival of 50 (= 100%) *Bairdiella icistia* Eggs in Antibiotic-Treated and Untreated Salton Sea Water at 17C and 35 ‰ S

Time from fertilization (hr)	Stage of development	Without antibiotics	With antibiotics
0	Fertilized eggs.....	100	100
13	Early embryo.....	86	84
22	Late embryo.....	78	84
35	Yolk sac larvae.....	16	72
46	Yolk sac larvae.....	0	62
60	Post yolk sac larvae.....	--	36

Three experiments with *bairdiella* eggs and larvae were conducted in 1970. Eggs were obtained by hormone-induced ovulation and temperature was controlled at a constant $21^{\circ} \pm 0.5$ C. In every instance there was a slight to strong increase in mortality rate with increased salinity (Table 4). In two experiments the lower salinities also resulted in similar increases in mortality rates (Table 4). When Penicillin was used (Table 5), the increased mortality rate appeared during the larval stage at 40‰ and in the embryonic stages at 45‰ and higher salinities.

TABLE 4—Percent Survival of *Bairdiella icistia* Eggs and Larvae at 21C in Different Salinities. (Eggs were produced by hormone-induced ovulation. No antibiotics were used in these experiments. n = ~ 100 fertilized eggs = 100%.)

Time from fertilization (hr)	Stage of development	Salinity (parts per thousand)							
		30	33.5	35	37.6	40	45	50	55
<i>Experiment 1</i>									
0	Fertilized eggs	100.0		100.0		100.0	100.0	100.0	100.0
13	Tail-bud embryo	36.5		72.3		35.9	38.0	19.4	0.0
21	Tail-bud embryo	35.6		66.3		33.0	35.0	7.8	--
30	Tail-free	29.8		56.4		23.3	22.0	4.9	--
36	Yolk sac larvae	24.0		51.5		18.4	16.0	0.0	--
42	Yolk sac larvae	18.3		50.5		17.5	12.0	--	--
47	Yolk sac larvae	18.3		50.5		17.5	12.0	--	--
<i>Experiment 2</i>									
0	Fertilized eggs		100.0	100.0	100.0	100.0	100.0	100.0	100.0
12	Tail-bud embryo		49.0	47.6	72.5	25.0	43.0	14.3	0.0
23	Tail-free		49.0	43.8	60.4	21.0	30.0	8.2	--
30	Yolk sac larvae		48.0	37.1	52.7	21.0	28.0	7.1	--
37	Yolk sac larvae		47.0	35.2	49.5	18.0	25.0	4.1	--
45	Yolk sac larvae		47.0	33.3	49.5	18.0	24.0	4.1	--
60	Post yolk sac larvae		14.0	0.0	17.6	0.0	0.0	0.0	--
<i>Experiment 3</i>									
0	Fertilized eggs			100.0		100.0	100.0	100.0	100.0
12	Tail-bud embryo			65.9		66.3	67.0	44.5	19.2
20	Tail-bud embryo			52.3		60.4	59.0	31.8	10.1
31	Tail-free			44.3		53.6	54.0	30.0	6.1
36	Yolk sac larvae			42.0		53.5	51.0	28.2	3.0
42	Yolk sac larvae			42.0		52.5	47.0	16.4	3.0
46	Yolk sac larvae			42.0		52.5	47.0	16.4	3.0

TABLE 5—Percent Survival of *Bairdiella icistia* Eggs and Larvae in Different Salinities. (Eggs were produced by hormone-induced ovulation. Penicillin-G, 50 ppm was used in each salinity. n = ~ 100 fertilized eggs = 100%.)

Time from fertilization (hr)	Stage of development	Salton Sea (S) (parts per thousand)				
		35	40	45	50	55
0	Fertilized eggs.....	100	100	100	100	100
13	Tail-bud embryo.....	92	94	81	58	11
20	Tail-bud embryo.....	92	91	78	55	4
30	Tail-free.....	89	90	73	48	3
36	Yolk sac larvae.....	88	89	72	48	2
56	Yolk sac larvae.....	17	1	1	0	0

Table 6 has similar data obtained with sargo embryos and larvae in 1968 and 1970. In the experiment performed in 1968 (Experiment 1), 50 surviving, normal-appearing embryos which had been fertilized in their appropriate salinities were observed over a 96-hr period. Mortality was virtually absent in 35‰ Salton Sea water but the rate escalated with increased salinity. In the late larval stage, only 8% (4 larvae) were alive at 96 hr and 50‰ whereas 90% (45 larvae) were alive in the control (35‰) Salton Sea water.

TABLE 6—Percent Survival of Sargo, *Anisotremus davidsoni* Eggs and Larvae in Different Salinities. (Experiment 1 was started with 50 fertilized eggs ($n = 50 = 100\%$) which survived 10 hr in each appropriate salinity. Eggs were obtained from spawning females caught in the Salton Sea in Experiments 1 (1968) and 2 (1970). In Experiment 3, eggs were obtained from hormone-induced ovulation. A variable number of fertilized eggs was used in each salinity in the latter two experiments ranging from 31 to 103 in Experiment 2 and 28 to 31 in Experiment 3.)

Time from fertilization (hr)	Stage of development	Salinity (parts per thousand)				
		35	40	45	50	55
<i>Experiment 1</i>						
10	Tail-bud embryo-----	100.0	100.0	100.0	100.0	100.0
25	Tail-free-----	90.0	92.0	80.0	66.0	24.0
52	Yolk sac larvae-----	90.0	90.0	68.0	52.0	10.0
73	Post yolk sac larvae-----	90.0	78.0	62.0	0.0	0.0
96	Post yolk sac larvae-----	90.0	8.0	0.0	0.0	0.0
<i>Experiment 2</i>						
0	Fertilized eggs-----	100.0	100.0	100.0	100.0	100.0
16	Tail-bud embryo-----	54.8	63.8	72.7	69.2	74.8
27	Tail-bud embryo-----	12.9	14.9	36.4	43.6	57.3
34	Tail-free-----	12.9	12.8	36.4	41.0	55.3
40	Yolk sac larvae-----	12.9	10.6	36.4	41.0	50.5
51	Yolk sac larvae-----	12.9	10.6	36.4	41.0	50.5
<i>Experiment 3</i>						
0	Fertilized eggs-----	100.0	100.0	100.0	100.0	100.0
14	Tail-bud embryo-----	71.0	81.8	19.4	21.4	0.0
19	Tail-bud embryo-----	64.5	77.3	19.4	0.0	--
32	Tail-free-----	58.1	40.9	9.7	--	--
38	Yolk sac larvae-----	48.4	40.9	9.7	--	--
44	Yolk sac larvae-----	48.4	4.5	0.0	--	--
65	Post yolk sac larvae-----	9.7	0.0	--	--	--
84	Post yolk sac larvae-----	0.0	--	--	--	--

Experiments 2 and 3 (Table 6), performed with sargo eggs obtained by hormone-induced spawning in 1970, similarly showed a clear detrimental effect of salinity on survival rate at 40‰ and higher.

Although antibiotics prevent the drastic mortality rates of embryos and larvae at salinities of 40‰ and higher, bairdiella and sargo embryos which survived under these conditions exhibited developmental abnormalities. Bent tails and the inability to swim straight after hatching were the most common signs of abnormal development.

DISCUSSION

Salton Sea water of 40‰ salinity apparently exceeds the upper tolerance limits of bairdiella and sargo to salinity during embryonic and larval development. In most experiments 40‰ was clearly detrimental to life at these early stages as reflected in increased mortality rates. When mortality was not accelerated in a few experiments, embryos at 40‰ S and higher were abnormally developed and produced larvae which did not survive beyond the yolk-sac stage. At 40‰ S fertilization success was usually lower, abnormal embryos developed from fertilized eggs, the mortality rate of eggs and larvae at salinity was accelerated over controls at normally experienced salinities, and any larva hatched out at 40‰ salinity or higher was also abnormal; these facts suggest that bairdiella and sargo will not reproductively survive a rapid change in salinity over their normal habitat, now about 37‰ S in the Salton Sea. However, it is still possible that slow acclimation and genetic adaptation of the adults to rising salinity will favor production of gametes that will survive and live normally. The experiments reported here can be logically extended to include (i) acclimation of adults to high salinities and artificial spawning to ascertain gamete viability, (ii) mortality rate of eggs and larvae from acclimated fish, and (iii) the effect of temperature on salinity tolerance of eggs and larvae. The fact that fertilized eggs sink in La Jolla sea water at 33.5‰ and float in Salton Sea water at 37.6‰, suggest that adaptation has occurred toward higher salinities. However, no information is available on the parent stock of bairdiella from the Gulf of California. Simmons (1957) found *Bairdiella chrysura* in the Laguna Madre of Texas only in salinities of 45‰ and less. Other sciaenids live in the Laguna Madre, Texas, at salinities up to 75‰ but probably do not spawn in water above 45‰.

ACKNOWLEDGEMENTS

We wish to thank Alex Calhoun (California Department of Fish and Game, Sacramento, California) for suggesting this problem to us and also Hiram Li, Jack Hanson, David Crear, and Irwin Haydock for material assistance at the Salton Sea.

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THE NEEDS OF FISHING FLEET OPERATORS IN TERMS OF MARINE
ECOLOGY, FISH DETECTION, COMMUNICATIONS,
METEOROLOGY AND NAVIGATIONAL AIDS

According to information gathered by the Food and Agriculture Organization of the United Nations, 1970 world production of fish and shellfish amounted to 69.3 million metric tons. Examination of historical records of world fish catches shows that the catch has increased steadily each year for the past 30 years. For example, total world catch in millions of metric tons of marine fish, crustaceans, mollusks, and other aquatic animals was about 18.0 in 1948, 27.5 in 1958, and 55.0 in 1968.

A number of estimates have been made of how much food the ocean can produce on a sustained basis. These estimates have been based on extrapolation of present trends and success in areas now heavily exploited to regions of the ocean yet unexploited and on energy flow through the marine food web. The former approach appears to give estimates much below those of the latter, however, the processes governing ocean productivity are imperfectly understood and much further study is needed to refine estimates now being made. Nevertheless, the present consensus among fishery scientists is that the production from the sea can be increased significantly, perhaps by a factor of 3 to 5 times that now being produced. It is expected that the greatest increases in catch will come largely from the pelagic plankton-eating fishes.

The ultimate amount of food that is harvested from the world oceans on a sustained basis will depend on proper management of the world fishing resources and improved fishery technology, notably an increase in efficiency of fishing operations through improvement of present methods and development of new and economical harvesting techniques.

Remote sensing from satellites holds great potential for assisting man in the rational utilization and increased production of ocean fisheries. Remote sensing from satellites may improve the performance of the fishing industry by increasing the fishery product output through increasing the exploitation of presently underutilized or unutilized species and by reducing costs on existing fisheries. There would appear to be two general ways in which an expanded system of satellite observations may assist fishing operations. The most dramatic would be the location of fish concentrations by the use of satellites. However, this is beyond the present state of the art and does not appear likely that satellites will be able to directly detect large near-surface schools in the near future. Probably the most important benefits that satellite observations may provide to commercial fishing are the observation and recording of environmental phenomena that are related to the abundance and distribution of fish stocks and the improvement of marine weather and sea conditions forecasting.

Fishermen have need for information concerning the distribution of sea surface temperature and ocean color and the location of oceanic boundaries. In addition timely, accurate forecasts of marine weather and sea conditions are

important for fishing operations. A brief description of how selected satellite measurements are used or can be used in fisheries is given in the following section.

Sea Surface Temperature

Sea surface temperature is one of the more important oceanographic measurements employed in fisheries oceanography research and in fish scouting operations. Fishes and other marine life have preferred temperature ranges, and temperature usually sets the limits of distribution of marine organisms. The optimum temperature range for distribution and fishing of tuna species is given in Figure 1. In addition, sea surface temperature is fundamentally related to many ocean processes which play important roles in determining the distribution and abundance of marine food and sport fishes. Knowledge of sea surface temperature over large areas is important in the detection and monitoring of ocean currents, water mass boundaries, upwelling zones, and certain air-sea interaction processes which influence the heat-balance of the ocean-atmosphere system.

Sea surface temperature measurements, along with marine meteorological observations, are made by merchant ships, fishing vessels, research vessels, and military vessels. The observations are radioed ashore in real-time and the data are disseminated to users over special teletype circuits. While this is a good and important scheme for obtaining sea surface temperature information, the distribution of the observations is mainly along shipping lanes and there are large ocean areas which are devoid of observations. Often these areas of scarce data are important fishing grounds, such as the eastern tropical Pacific.

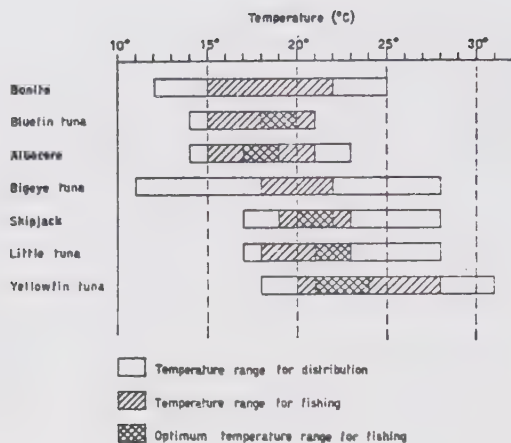


Figure 1. Temperature range for distribution and fishing of tuna species (from Hela, I. and T. Laevastu, 1970. Fisheries Oceanography. Fishing News (Books) Ltd.).

The eastern tropical Pacific is an important fishing region for tunas, billfishes, and other fishes. For example, the annual U.S. tuna catch in 1971 from this region amounted to about 205,000 tons with an ex-vessel value of about 82 million U.S. dollars. Japan, and several Latin American countries also have valuable tuna and other fisheries in the eastern tropical Pacific.

Information concerning the distribution of sea surface temperature, especially delineations of regions of sharp temperature gradient which are called sea surface temperature "fronts", is of great assistance to fishermen in locating potentially good areas of fishing in the eastern tropical Pacific. Ocean temperature information is also needed for long range fishery planning, and population models require ocean temperatures for predicting the location and availability of the tunas in the eastern tropical Pacific. Also detailed sea surface temperature data over the spawning grounds in the central Pacific are essential in estimating the recruitment of future tuna stocks into the fishing grounds.

A plot of the number of sea surface temperature observations received from surface vessels during a 1-week period from the eastern tropical Pacific between 30° N to 5° S and the American coast and 140° W, and a contour plot of the data are shown in Figures 2 and 3, respectively. It is readily apparent that the number of reports is limited, observations are confined mainly to the shipping lanes, and there are large areas where no observations are available. Also, because the data coverage is so sparse, it is not possible to locate the presence of local sea surface temperature "fronts."

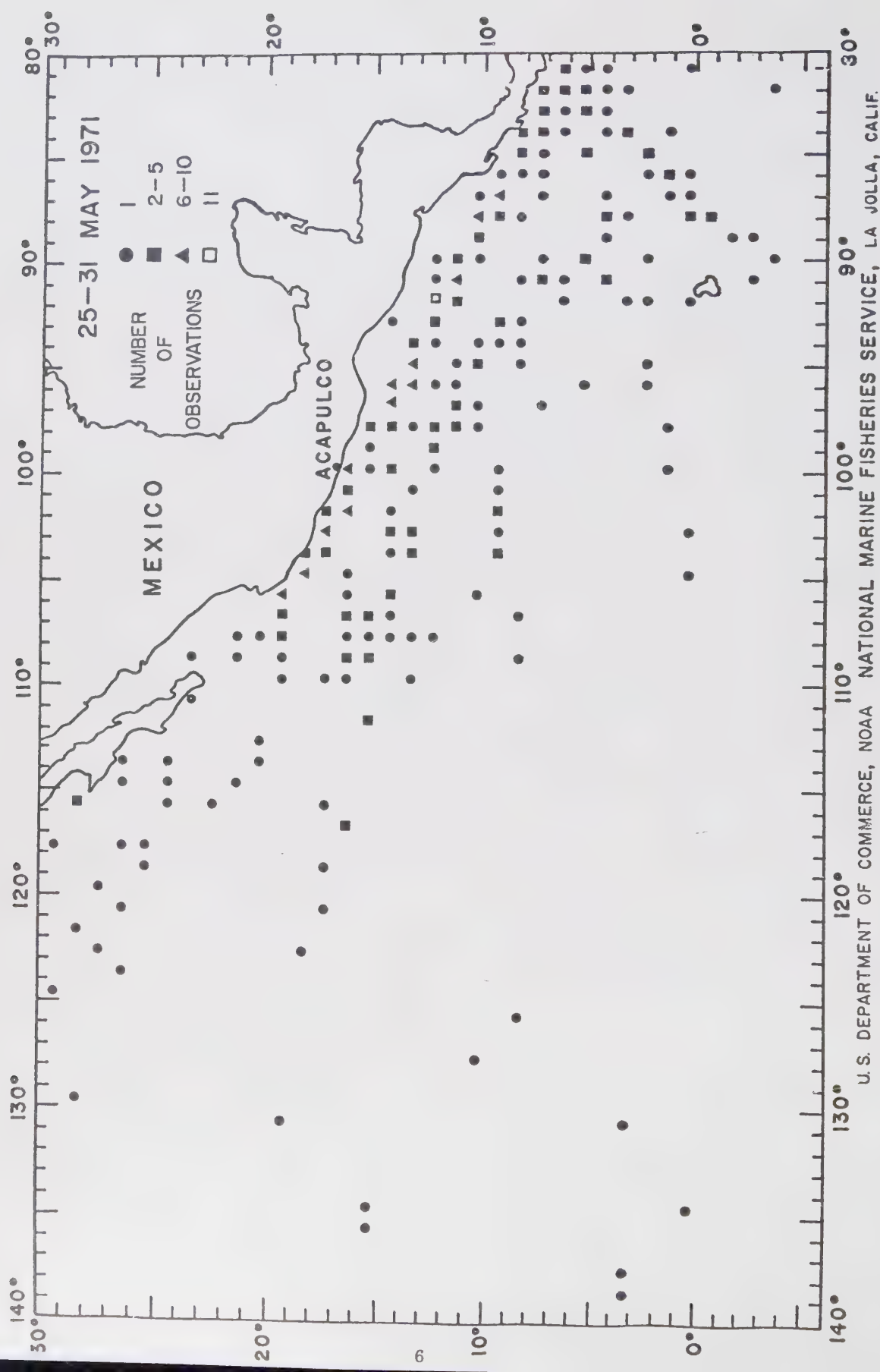


Figure 2. Number of ship reports received from eastern tropical Pacific during May 25-31, 1971.

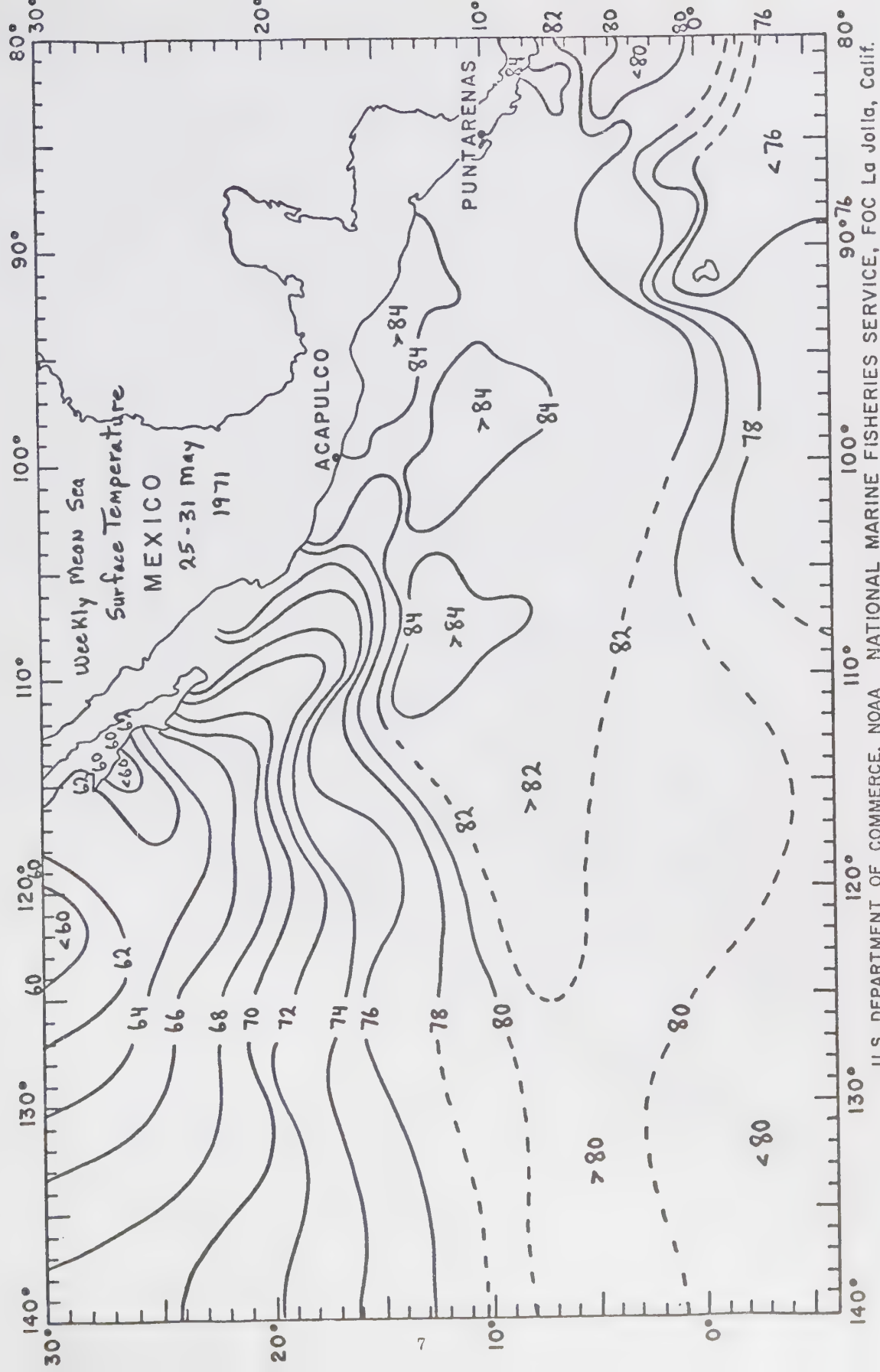


Figure 3. Distribution of sea surface temperature in eastern tropical Pacific, May 25-31, 1971.

A satellite equipped with the proper sensor may provide an ideal means of monitoring and filling in the gaps of data in the distribution of sea surface temperature in the eastern tropical Pacific and other ocean areas. With the ability of a polar-orbiting satellite to repeatedly map the entire globe in 12-hour intervals, remote-sensing of sea surface temperature from satellites could provide valuable synoptic data to evaluate short-term variations in the distribution of sea surface temperature and locate the presence of sea surface temperature "fronts."

Several satellites have been equipped with radiometers for making sea surface temperature measurements using infrared techniques and under certain conditions good results have been obtained. A chart showing the distribution of sea surface temperature based on measurements received from infrared sensors aboard NOAA-1 is shown in Figure 4. The measurements shown in Figure 4 are about 8° C above those reported by ships that were in the area at the same time the observations were made by the satellite. The higher satellite temperatures are due to radiometer calibration techniques. The chart has extremely useful applications to fisheries because it shows small-scale sea surface temperature frontal structure and by having some prior knowledge about the temperature range and distribution in the region and a few ship reports, numbers could be assigned to the isotherms that would be more representative of the absolute temperatures.

There are limitations to infrared measurements of sea surface temperature from satellites. The infrared radiance method involves the assumption of a homogeneous,

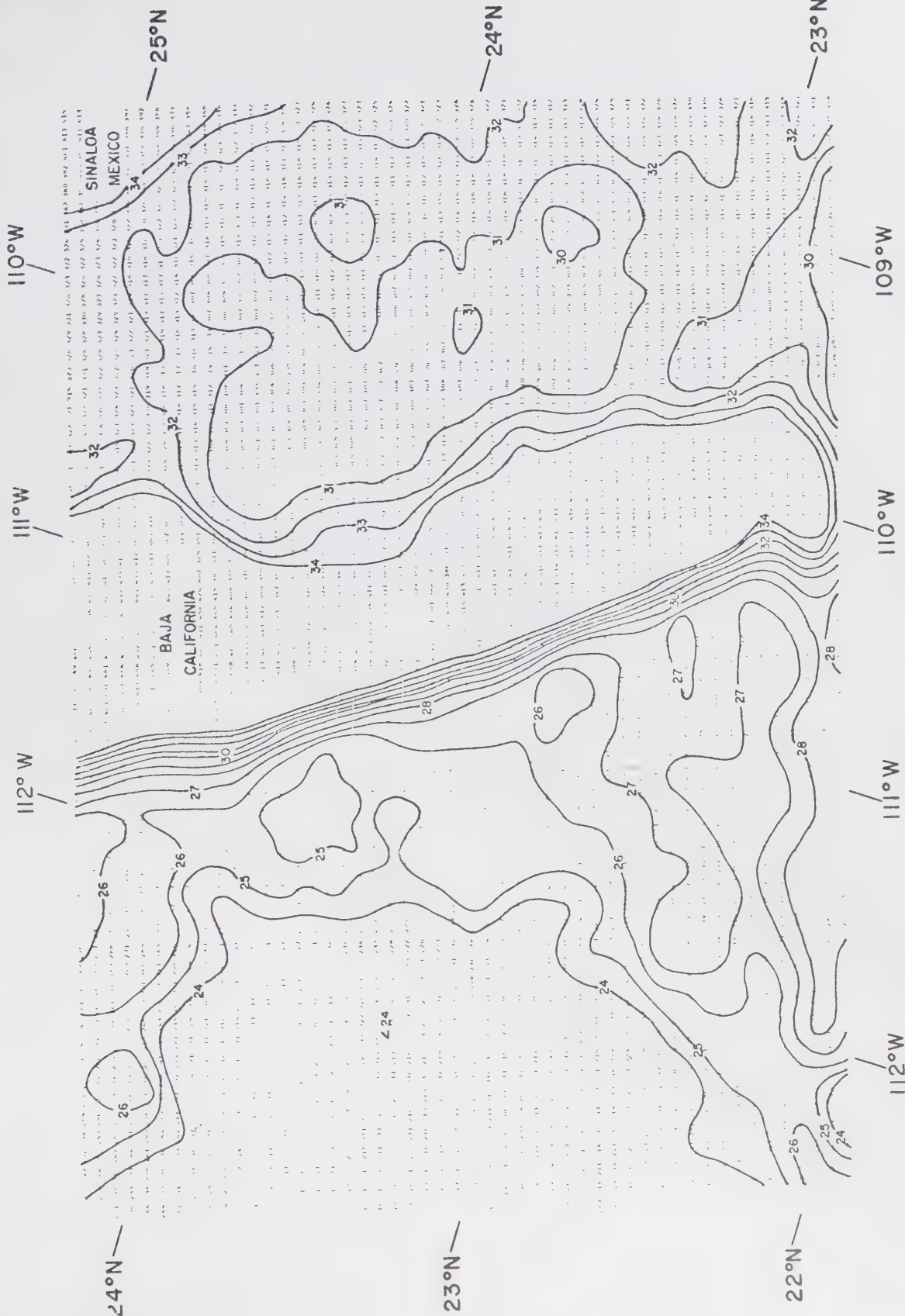


Figure 4. DRR map of surface temperature (°C) for NOAA 1 (scanning radiometer No. 2) on May 6, 1971.

non-transparent target that fills the radiometer field of view. This means that severe contamination of the radiation measurements is introduced by clouds and that this method of measuring sea surface temperature is limited to cloudless areas. In order to determine whether clouds contaminate the radiation measurements, simultaneous cloud photographs from the same satellite are necessary for proper interpretation of the radiation data. In addition because of atmospheric attenuation due to water vapor, which is non-uniformly distributed in space and time in the atmosphere, proper corrections must be applied to satellite radiance measurements in order to derive correct sea surface temperatures.

In spite of limitations, the information concerning the distribution of sea surface temperature derived from infrared measurements made from satellites can be very useful to fisheries. However, the total potential of sea surface temperature measurements from satellites will not be realized by fisheries until sensors are developed which will give all-weather measurements. This will enable sea surface temperature measurements to be made from satellites in regions of upwelling, where most of the world's most important fishing areas are located, and other cloud-covered areas which are important fishing grounds.

The development of microwave radiometry for remote measurements of sea surface temperature and other applications is underway. Experiments using airborne microwave sensors are yielding encouraging results and indicate that an all-weather capability of measuring sea surface temperature from space platforms may be possible in the near future.

Ocean Color

It appears quite probable that spectral measurements of backscattered light from the ocean surface will be made by satellites in the near future and provide information on ocean color. The ability to measure ocean color with high accuracy on a global basis by satellites may provide a new and useful tool for locating areas of high biological productivity in the world ocean and lead to the discovery of exploitable fishing grounds.

Ocean color can be used to delineate water masses, to trace currents, and to determine the amounts of chlorophyll, pollutants, and other important materials in the ocean. In addition ocean water color is also used by fishermen in planning fishing strategy and in deciding where to fish. For example, some Japanese tuna fishermen use water color measuring kits to find water of optimum color before setting their lines. Salmon and albacore tuna fishermen fishing in Pacific waters off the coast of North America often will use color "fronts" as one of the indicators of an area of potentially good fishing and many fishermen have reported that high catches are often made in the vicinity of ocean color "fronts." Water color, as an indicator of coastal currents may also assist in the determination of migration paths of shrimps in the Gulf of Mexico and may be useful in predicting their abundance and distribution. An oceanographic analysis of a photograph taken during the GEMINI flight series determined that the shrimp catch in the Gulf of Mexico was highest in turbid water.

Since chlorophyll is associated with living plants, spectral measurements of chlorophyll concentration may be used as an index of the amount of phytoplankton present in ocean water. Phytoplankton - microscopic, floating plants - form the base of the marine food chain and regions of high phytoplankton abundance can support large populations of herbivores and of successive links in the food chain, including those which are of economic importance to man. Thus, chlorophyll may be used to indicate the presence of potentially productive areas. Remote spectral measurements of the proper wavelengths for estimating chlorophyll concentration have been successful from low flying aircraft and have shown that increasing amounts of chlorophyll are associated with a relative decrease in the blue portion of the spectrum and an increase in the green. The absorption spectrum of a variety of marine phytoplankton is shown in Figure 5.

Investigation is underway to extend the airborne instrumentation and technique for measuring chlorophyll to satellite application. Providing certain atmospheric interference can be eliminated, or identified and allowed for, spectrometric procedures from satellites for estimating chlorophyll concentration appears probable.

Detection of Oceanic Boundaries

The detection of boundaries between water masses, currents, and other oceanic discontinuities could have important applications to marine fisheries. The migration routes followed by some pelagic fishes are thought to be related to oceanographic boundaries. High biological productivity is often associated with

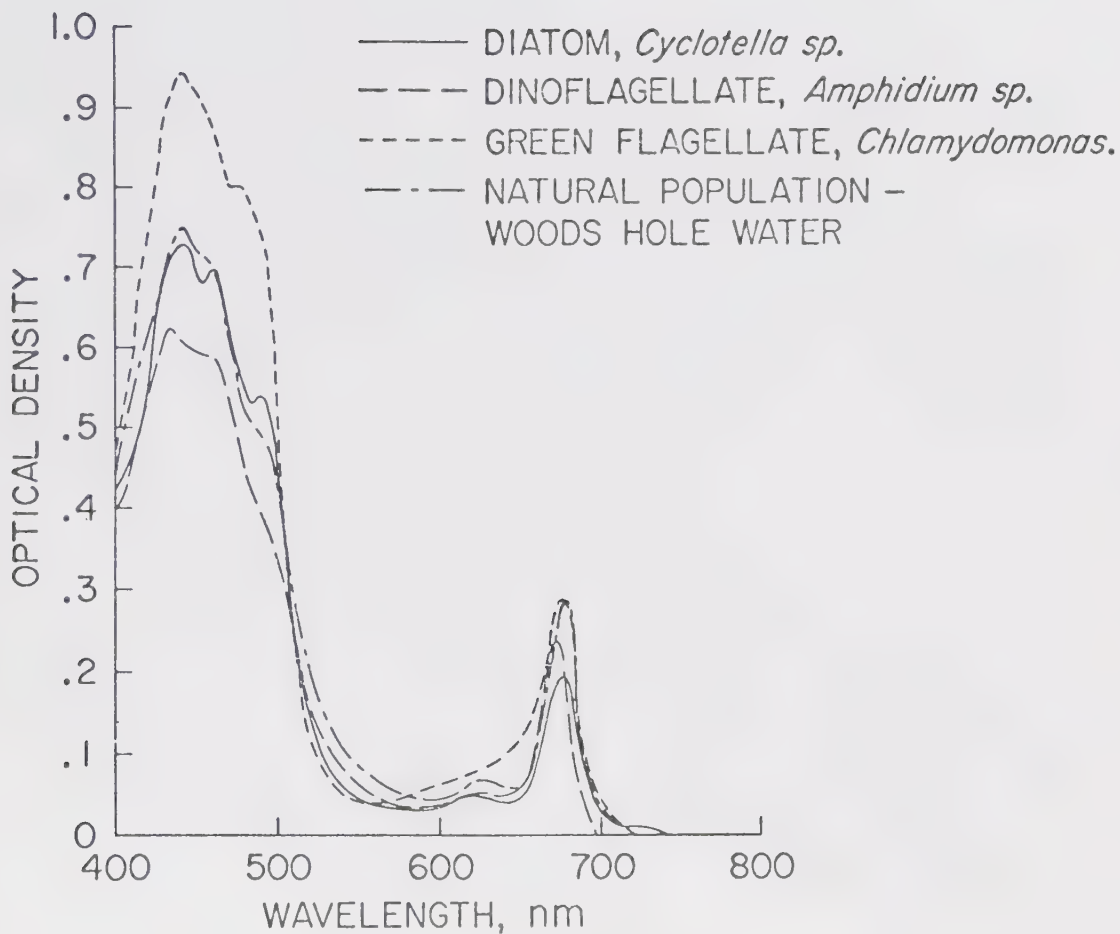


Figure 5. Absorption spectra of a variety of marine phytoplankton (from Yentsch, C. S., 1959. The influence of phytoplankton pigments on the colour of sea water. Deep-Sea Research 1: 1-9).

some types of oceanic boundaries, resulting in good feeding conditions for fishes. Thus, areas of good fishing are often found in the vicinity of oceanic boundaries and fishermen spend much looking for them as a place to fish. In addition, certain marine organisms, including some fishes, are limited to specific water masses and the delineation of the water mass makes it possible to predict the distribution of species confined to it.

Studies have shown that present satellite photography can provide information useful in detecting pronounced oceanic discontinuities, essentially from contrasting sea surface temperature conditions. The location of boundaries can be inferred visually from photographic results from satellites by characteristic modifications of existing cloud patterns as caused by differential sea surface temperature patterns and the concurrently induced local vertical circulations in the lower atmosphere. However, this method is not highly accurate because the ocean boundary and the cloud boundary do not always coincide, and may be displaced several kilometers from each other. The method has been successful in delineating the general location of boundaries of several major ocean currents including the Gulf Stream, the Brazil and Falkland Current boundary, the boundary between the Oyashio and Kuroshio Currents and the western boundary of the Agulhas Current.

Assuming successful sensor development for satellite application, the simultaneous measurement of sea surface temperature and ocean color may be used to locate oceanic boundaries on a global scale in the future. Simultaneous measurement of these two properties from airborne sensors has been successfully used to delineate oceanic boundaries.

Meteorological Aids

Weather conditions are extremely important to the safety and efficiency of fishing operations and timely accurate weather forecasts are extremely important to fishermen. Video photographs received from cameras pointed toward the earth aboard orbiting and geostationary satellites are proving to be of great assistance to meteorologists in making weather predictions. This has been especially true in those instances where photographs from satellites are being used as an aid in making marine weather forecasts for fishermen. For example, at the National Marine Fisheries Service, Southwest Fisheries Center in La Jolla, California, an Automatic Picture Transmission (APT) satellite receiving system is being used to monitor conditions over the fishing grounds in the eastern tropical Pacific. The fishing grounds extend westward from the principal shipping lanes along Central America, and the APT satellite coverage makes it possible to infer, more accurately, weather and sea conditions in areas where surface observations are sparse. The APT satellite photographs are extremely useful in locating areas of bad weather along the Inter-tropical Convergence Zone and elsewhere, and in tracking the movements of tropical storms and hurricanes. Also, when combined with surface ship observations, the APT satellite photographs are of great assistance in identifying areas of good weather and probable improved fishing conditions.

Based on the analysis of APT satellite photographs and surface observations from merchant and fishing vessels, two charts (Figures 6 and 7) containing oceanographic and weather information tailored to fishermen's needs are being transmitted daily via radio facsimile broadcast to vessels on the fishing grounds in

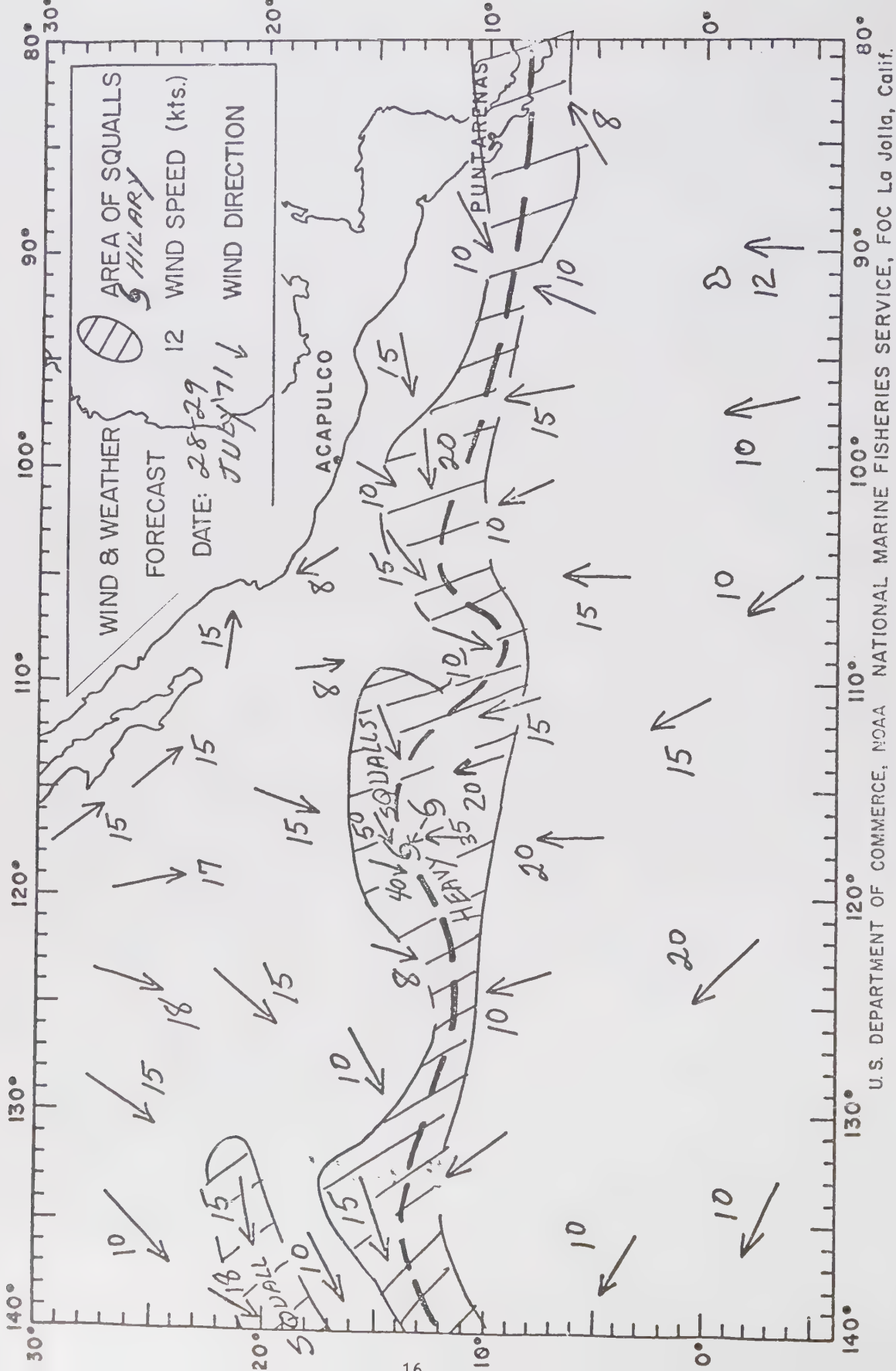


Figure 6. Wind and weather forecast chart.

the eastern tropical Pacific. Sea state information including swell direction and height, wind-wave height and, once each week, a 7-day sea surface temperature analysis, is given on one chart. A second chart provides information on direction and speed of surface winds, location and direction of movement of tropical storms, location of areas of squalls and other inclement weather conditions, and location of the Intertropical Convergence Zone. Within the very near future a weekly analysis of thermocline depth and summaries of catch information will be included on the charts. Eventually the location of ocean surface temperature fronts indicated by infrared temperature measurements made by orbiting satellites and received by the APT installation at the Southwest Fisheries Center will be added to the charts.

The fishery-advisory service to tropical Pacific tuna fishermen is being performed on an experimental basis as a means of obtaining valuable environmental data from fishing vessels and to provide fishermen with information which may assist them in making tactical fishing decisions. Fishermen are provided radio facsimile recording equipment for copying the charts with the agreement that they radio ashore environmental data. The environmental data collected by fishermen are used in the preparation of the fishery-advisory charts and in research concerning the development of fishery-forecasting techniques and methods for tropical tunas currently underway at the Southwest Fisheries Center.

Navigation and Locating Electronically Equipped Objects

Methods of navigation used by fishermen range from visual using the human eye unaided or aided by instruments such as telescopes and sextants to highly sophisticated electronic navigation systems such as Loran and Omega. To my

knowledge no U.S. fishing vessels are equipped with satellite navigation equipment and it is unlikely that U.S. fishing vessels will use satellite navigation equipment in the near future because of high cost, complexity of operation, and difficulty of obtaining service in small ports.

There is a great potential in fisheries research to use satellites for locating electronically equipped objects and communication of information to shore. This use of satellites could extend and improve geographic coverage of data and make it possible to obtain data, particularly below the surface, on a real-time or synoptic basis. It could also be used to track movements of fishes and other marine animals, and improve our understanding of their migration patterns.

Summary

Remote sensing from satellite technology as applied to fisheries and fisheries-oceanography is an emerging technique. Nevertheless, the degree to which satellite remote sensing may assist is becoming more positive. Measurement of sea surface temperature from orbiting satellites with infrared radiometry has been demonstrated and the development of an all-weather thermal capability using microwave radiometry is expected to provide basic scientific data for the benefit of fisheries. Measurement of ocean color and sea state on a global scale by satellites appears feasible. In addition it appears possible to monitor ocean currents and boundaries and areas of upwelling from earth orbiting satellites.

One of the greatest potential applications of remote sensing from satellites to fisheries would be the simultaneous determination of sea surface temperature

and ocean color. Synoptic measurements of temperature and chlorophyll could provide valuable information for locating potential areas of good fishing. For example, fishery-oceanography studies off the Pacific coast of Baja California have shown that tunas there feed almost exclusively on pelagic red crabs, Pleuroncodes planipes. The red crabs are herbivores and are most abundant in and adjacent to areas of localized upwelling where phytoplankton abundance is highest. Thus remote sensing of chlorophyll could provide an indirect assessment of the distribution and abundance of potential tuna forage and sea surface temperature measurements could be used to locate which of the forage-rich waters are of optimum temperature for tuna. Correlations between fish population and water color and temperature have also been found in the region of the Columbia River plume off the Pacific Northwest coast of the U.S. Color measurements in conjunction with temperature measurements could also be used to delineate water mass boundaries and currents.

A strong point should be made, however, if the information acquired by sensors aboard satellites is to be usefully applied to fisheries, each data acquisition (sensor) package will require unique data management and analyses techniques and equipment to convert the information to usable forms. Likewise an effective communication network will be required to transmit the information to users.

May 19, 1972

OBSERVATIONS OF SHARKS ATTACKING PORPOISES

(Stenella spp. and Delphinus cf D. delphis)

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INTRODUCTION

Records of actual observations of shark predation on porpoises are rare. Wood, Caldwell and Caldwell (1970) summarized the most significant observations to date and discussed the evidence that sharks do sometimes prey on porpoises (e.g., crescent-shaped scars on live porpoises and porpoise remains in shark stomachs). They also indicated, however, that it is impossible to determine what proportion of the scarred porpoises suffered the bites when they were young and susceptible to attack and whether the porpoise remains found in shark stomachs were from animals already dead before being eaten. They speculated that healthy, uninjured adult animals are less likely to fall prey to shark attacks than sick, injured or young animals. One of us (Perrin, 1968) has previously reported seeing sharks feeding on porpoises injured during tuna purse seining operations.

During the past several years, we have collectively made seven trips to the eastern tropical Pacific aboard commercial tuna purse seiners. We have also observed five experimental net sets made in local southern California waters by chartered seiners. In the shark-rich eastern Pacific, in association with a fishery in which porpoises are frequently entangled and injured or killed (Perrin, 1970), there are numerous opportunities to observe shark predation on the spotted porpoise, Stenella graffmani, and spinner porpoise, Stenella cf S. longirostris. In the experimental sets in local waters, there were similar opportunities to observe shark predation on white-bellied porpoises (Delphinus cf D. delphis). Although the majority of the observations were of sharks feeding on dead porpoises, several attacks and attempted attacks on living animals were seen. This paper summarizes all observations to date and discusses the threat that sharks pose to these three pelagic odontocetes.

OBSERVATIONS

The most common kind of incident observed by all of us was sharks feeding on dead porpoises. In the tropical fishing grounds, incidents of this kind occurred at two times: during the actual fishing operations, and at night when the vessel was drifting on an active fishing ground. Of the porpoises that are killed during a net set, only the youngest animals float, presumably because of a higher percentage of blubber in the total body weight. Those that do remain near the surface almost invariably float vertically with the snout out of the water. It was on these dead floating animals that the majority of observed attacks occurred. Although the specific details vary somewhat, the following excerpt from a fishing log describes a fairly typical pattern of attack:

"The body of a juvenile spotter (S. graffmani) was floating approximately 50 meters off the stern. Only the porpoise's beak was projecting from the water. Two sharks of unidentified species, approximately 4 feet in length, circled the body for 10 to 20 seconds at a close range of within 2 feet. One attacked, followed immediately by the other. The body bobbed violently for a few seconds, discolored the water, and then sank from sight." (Field notes of Garvie.)

Although the majority of such incidents occurred outside the pursed net, sharks were often seen inside the net and occasionally constituted part of the catch. In at least one instance, a dead Delphinus was attacked and eviscerated by a 4-foot mako shark (Isurus lamma) inside the net. Although no other instances of sharks biting dead porpoises inside the net were recorded, all of us have seen boated tuna and porpoises that had been mutilated by what could only have been sharks.

We also observed sharks feeding on dead porpoises when the tuna boats were drifting at night in an area rich with fish. Since the decision to drift all night generally follows a successful day of fishing, we were frequently on the deck at this time dissecting porpoise specimens that had been saved from the day's catch. On those occasions, it was not unusual to see sharks cruising the area. As the remains of dissected carcasses were dumped over the side, sharks were seen to move in their direction. One such incident was recorded in detail:

"As we were drifting, several sharks, including a 3-meter hammerhead shark Sphyrna sp., were moving lazily around the boat. I had been dumping remains over the side for half an hour, but not taking time to watch what happened to them. At 2000, when I completed the last dissection and dumped the carcass in the water, I stood at the gunwales to watch. As soon as the carcass hit the water, I saw the hammerhead swim rapidly toward it and rip most of one side of it away before it had been in the water 15 seconds." (Field notes of Leatherwood.)

Although almost all of the feeding observed was on dead animals, four instances of attacks on living Stenella (and at least one unsuccessful attempted attack on a Delphinus) were observed: two on apparently uninjured spotters; one on a live but entangled and struggling spotter; and the last on a live but probably injured spinner.

In the first instance of an attack on an uninjured animal, "a 4.5 foot male, which had been hauled aboard with the fish, was recovered and thrown over the side. Though he was active on the deck and ventilated well, once in the water, he blew only once and began to swim away sluggishly. When he was less than 35 yards off the bow, he was bitten in two by a shark which showed only its dorsal fin, so its size and species were undetermined. The remainder of the porpoise sank through the bloody water and out of sight." (Field notes of Leatherwood.)

In the second instance, "fishermen pulled a live adult female from the brailer and threw her over the side. As she was swimming away, a large shark, with a robust body and a sharply-pointed head, came from deep below the boat and bit the porpoise's midsection. The porpoise sank slowly and was hit several more times by smaller sharks before what was left of her sank out of sight." (Field notes of Leatherwood.)

In neither case did the animals have any apparent injury, although the first may have been suffering from the "capture shock" so often observed in

newly captured pelagic cetaceans. The second was quite active and began moving rapidly away from the boat as soon as she was put over the side. In order to attack her, the shark had to move very quickly on an intercept course.

The third instance involved a porpoise that was "gilled" in the net. "Entrapped near the corkline, the porpoise was thrashing violently. Suddenly, the thrashing stopped and the water became stained with blood. When the net was brought aboard, the porpoise, a juvenile spotter, was pulled on the deck and found to have been eviscerated completely by what looked like three bites from a large shark. The shark must have been inside the net at the time of attack, since the porpoise was entangled from the inside and the net was not torn. There were also some tuna in the net which had been bitten by sharks. Two species of sharks were also brought aboard. One large individual, 7 feet long, with a blunt snout and a rounded, white-tipped dorsal fin, probably Carcharinus longimanus, was the only one that appeared capable of inflicting the bite wounds described." (Field notes of La Grange.)

The other attack on a living but probably injured animal involved a spinner that was entangled in the net. "He was still breathing well when I pulled him from the net pile, tagged him, and put him over the side. Once in the water, he blew twice, all the time drifting towards the bow in the strong current; before he could recover and swim away, he was hit by an 8-foot shark with a black-tipped dorsal fin and killed. Although when I put him in the water he was still able to move both pectoral fins and flukes and had no obvious external injuries, there is an excellent chance that this animal had sustained internal injuries." (Field notes of Leatherwood.)

In addition to these four successful attacks on Stenella, unsuccessful attempted attacks by a mako shark on Delphinus were observed. The shark, trapped inside the closing net with nearly 1000 porpoises, repeatedly chased live adult porpoises for a few yards. In all instances observed, however, the porpoise escaped.

DISCUSSION

It was interesting to note that despite the optimum conditions for creating a feeding frenzy (i.e., the abundance of sharks and potential prey both inside the pursed net and around the boat during fishing operations and the discharge of bloody fishing brine from the fish storage wells) no frenzies were observed. In the four cases of attack cited above as well as in the numerous feedings on dead fish and porpoises, the sharks' movements were deliberate. Individual porpoises were apparently being eaten one at a time, and even though several porpoises might be floating close together, the sharks seemed to finish one as a group before starting on another.

None of the feedings on dead porpoises are suprising; neither, perhaps are the few attacks and attempted attacks on living animals in the circumstances of the tuna set. But they do raise the important question as to whether sharks normally pose a significant threat to spinner, spotter porpoise, or white-bellied porpoise or whether they are simply more bold in the atmosphere of confusion or

taking advantage of the accessibility of the porpoises. Several points are relevant. Sharks are frequently found around the tuna boats during sets, sometimes showing up suddenly even though none may have been seen the entire day. Philippe Cousteau (pers. comm., 1967) indicated that in dives under porpoise herds over several years, the divers of the CALYPSO very frequently found tuna and sharks associated with moving porpoise schools. Similarly, on two successive days off Coronado Island, California, small blue sharks and at least two mako sharks were seen swimming with a herd of Delphinus delphis. One 114 cm female porpoise taken during a set on that herd bore healed and partly healed shark scars behind the blowhole, around and below the right eye, on the right side of the melon and on the underside of the jaw (Fig. 1). Though no teeth were found in dissection of the tissue around the scar, the jaws from a 4-foot mako taken during the same set approximately fit the outline of the scar, indicating that a shark of similar size may have inflicted the bites. Of the 85 porpoises from this herd examined in 2 days, this was the only individual that bore a healed shark scar.

Another Delphinus, a 168 cm female captured, radio tagged, and released near San Clemente Island, March 9, 1971, also bore a healed shark scar on the right side of the tail stock. Of over 30 animals captured, tagged, and released to date (Evans, et al., 1972) only this animal bore evidence of a shark bite.

Of all the porpoise specimens examined on the deck during the six separate cruises to the eastern tropical Pacific fishing grounds, none bore scars positively identifiable as shark bites. This observation is consistent with the Caldwell's findings for 11 species of pelagic cetaceans (Wood et al., 1970) and the combined observations tend to support the suggestion that, in the open sea, healthy adult porpoises are highly unlikely to fall prey to shark attacks. Spinner, spotter and white-bellied porpoises are fast swimmers (to at least 14 knots) and could reasonably be expected to out-maneuver most sharks in open water. The absence of scars, however, might also be interpreted to indicate that any attacks that do occur are fatal. The question of the importance of sharks as natural predators of pelagic porpoise remains open and can only be further clarified by extensive observations of the natural interactions of these animals.

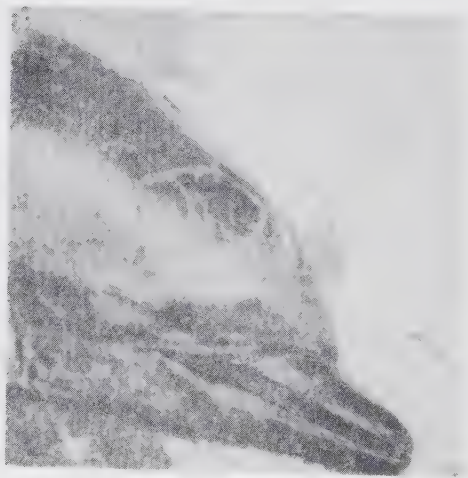
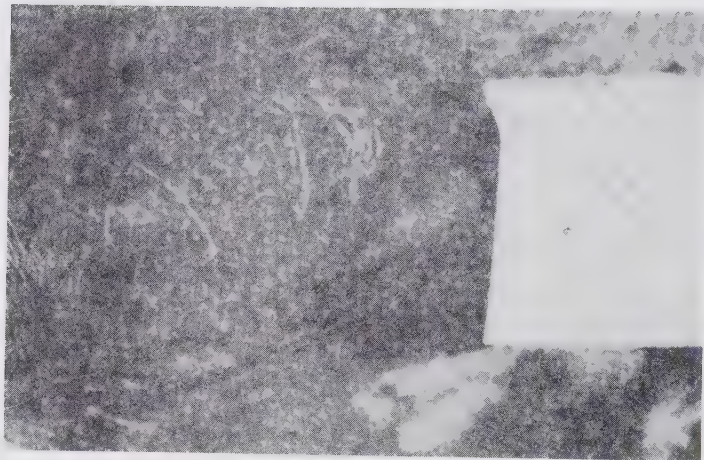


Figure 1. Two views of the head of a 114 cm Delphinus delphis showing healed and partially healed scars attributed to bites by a mako shark.

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MESH RETENTION OF LARVAE OF *SARDINOPS CAERULEA* AND *ENGRAULIS MORDAX* BY PLANKTON NETS

WILLIAM H. LENARZ¹

ABSTRACT

Mesh retention of the standard plankton sampling gear used by the California Cooperative Oceanic Fisheries Investigations between 1949 and 1968 for larvae of the Pacific sardine (*Sardinops caerulea*) and northern anchovy (*Engraulis mordax*) was estimated by comparing catches made by the standard gear with a gear that retains larvae of all sizes. The results indicate that 67% of sardine larvae and 60% of anchovy larvae are retained by the meshes of the standard gear. The standard gear was replaced by a similar gear in 1969. Apparently all anchovy larvae are retained by the new gear. The new gear is the same as the old gear except for the netting. The netting of the new gear is constructed from 0.505-mm mesh width nylon while the netting of the standard gear was constructed from 0.55-mm mesh width silk. Catch curves of anchovy and sardine larvae corrected for escape through meshes revealed no evidence of a critical period.

Although fisheries literature contains numerous examples of estimates of mesh retention of fish by commercial fishing gear, there is little quantitative work on mesh retention of fish larvae by plankton gear. A review of such studies by Vannucci (1968) revealed only three papers containing quantitative estimates of mesh retention by plankton gear. The lack of knowledge on this subject can cause serious errors when comparing the estimates of abundance of fish larvae made from samples taken by different sampling gears or of two or more species of fish larvae by the same gear.

This paper presents estimates of mesh retention of larvae of the Pacific sardine (*Sardinops caerulea*) and northern anchovy (*Engraulis mordax*) by plankton nets that have been used by the CalCOFI (California Cooperative Oceanic Fisheries Investigations). Estimates are made of the errors that result because mesh retention is ignored when the relative abundance of the two species is calculated and when abundance of the anchovy is computed using data from two quite similar types of sampling gear. Finally the catch curves of the two species are examined for evidence of the critical period proposed by Hjort (1926).

Several authors have noted that small larvae of the Pacific sardine and northern anchovy are not completely retained by the meshes of the plankton nets used by the CalCOFI, but did not have the necessary data to make quantitative estimates of the retention rates. Ahlstrom (1954) noted that small sardine larvae were not fully retained by the meshes of the net in use at that time. Ahlstrom (personal communication) attempted to obtain a measure of the retention rates with a series of paired plankton samples made with a regular CalCOFI net and a net with a finer mesh, but failed to capture an adequate number of sardine larvae. Isaacs (1965) concluded that anchovies up to 7.75 mm were not fully retained by the meshes. He attributed differences in the form of catch curves of anchovy larvae in different years to changes in the minimum size of complete retention. Murphy (1966) stated that anchovy larvae are undersampled "... by a factor of about 2, relative to sardines, i.e., they tend to pass through the mesh of the net to a marked extent." He did not describe his method of obtaining the estimate but later informed me (Murphy, personal communication) that he based his conclusion on comparison of catch curves with hypothetical curves based on the assumption of exponential mortality. Lenarz (in press) estimated that

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northern anchovy larvae were undersampled by a factor of 3.4 relative to sardine larvae because of differences in retention rate and rate of decline in catch with increase in size. His estimates of retention rates also were based on differences between observed catch curves and hypothetical curves based on a constant rate of decline.

METHODS

The data for this study on fish larvae were taken from CalCOFI plankton tows. From 1949 to 1968, CalCOFI used a single silk net (type 1) of 0.55-mm mesh with a 1-m diameter mouth opening. During 1966-68 this net was paired with one of nylon of 0.333-mm mesh (type 2) with a 1/2-m diameter mouth opening. In 1969 the netting of the larger net was replaced with monofilament nylon netting of 0.505-mm (type 3). The variance of mesh width of the type 3 net is considerably less than that of the type 1 net. Other details of the net characteristics are available from Smith². The nets were lowered and raised obliquely at a rate of 1.5 knots to a depth of 140 m in 1966-1968 and to 210 m during 1969. Since very few anchovy or sardine larvae occur below a depth of 140 m, the change in depth should make no difference in the results of this study. Other details of sampling are described by Ahlstrom (1966).

All sardine and anchovy larvae in each sample were identified and measured to the nearest 0.5 mm, standard length. The data revealed evidence of varying degrees of personal bias towards favoring measurements of whole millimeter rather than half millimeter. Sette (1950) was aware of the potential for this type of bias in measuring adult fish and stated: "... to avoid personal bias in favor of whole or half centimeter marks, the measuring scale had uniform graduation marks and they were serially numbered. In addition to avoiding bias, this had the advantage of giving two digit numbers for all listings and computations, the data being divided by two for conversion to centimeters at the final stage of work." Perhaps it would be

prudent to follow the advice of Sette, if 0.5 mm accuracy is desired. Evidence of personal bias in measuring the smallest sizes of larvae was also noted. Since the smallest larvae are often distorted, it is difficult to make objective measurements. Because of the above described biases, measurements of the larvae are grouped into the intervals shown in Tables 1 and 2. Larvae captured by the type 2 net were multiplied by the ratio of volume of water sampled by the type 1 net to the volume of water sampled by the type 2 net to adjust for the smaller size of the type 2 net. The samples were chosen on the basis of the presence of sardine larvae or moderate numbers of anchovy larvae.

The following equations, using the notation of Regier and Robson (1966), were used to estimate mesh retention of the type 1 net

$$n_{ijk} = S_{ij}n_{2jk} + e_{jk} \quad (1)$$

where n_{ijk} = number of larvae of size L_j caught by type i net in k th sample.

s_{ij} = mesh retention of type i net to larvae of size L_j , i.e.,
 $s_{ij} = n_{ij}/N_j$

where N_j = either absolute or relative number of larvae of size L_j in the population.

e_{jk} = error term that is assumed to be normally distributed and independent of n_{2jk} .

The use of equation (1) to estimate mesh retention of the type 1 net implies the assumption that s_{2j} is 1 for all j , i.e., $N_j \approx n_{2j}$. Preliminary analysis of data obtained from a series of paired samples of the type 2 net and a finer meshed net indicates that this assumption is valid for northern anchovy and Pacific sardine (P. E. Smith, personal communication). This method of estimating S_{1j} from a known or estimated N_j is noted as the "direct approach" in the terminology of Regier and Robson (1966).

The least squares estimate of s_{1j} is given by Cochran (1963) as

² Paul E. Smith, National Marine Fisheries Service, Southwest Fisheries Center, La Jolla, Calif.

TABLE 1.—Catches of northern anchovy larvae by type 1 (0.55-mm mesh) and type 2 (0.333-mm mesh) nets for each sample.

Cruise	Station	Net type	Standard length							
			2.5	3.75	4.75	5.75	6.75	7.75	8.75	9.75
6601	93.35	1	141	175	38	18	17	14	4	0
		2	994.950	55.275	22.110	25.795	14.740	0.000	0.000	0.000
6601	103.29	1	95	121	291	145	45	23	10	5
		2	164.250	141.255	351.495	128.115	42.705	22.995	13.140	3.285
6601	120.24	1	22	51	66	62	30	21	15	4
		2	32.330	54.961	109.922	42.029	42.029	32.330	22.631	12.932
6601	120.35	1	25	59	37	17	11	0	0	0
		2	36.113	68.943	36.113	16.415	0.000	0.000	0.000	0.000
6607	113.50	1	3	1	1	1	0	0	1	0
		2	9.716	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6607	117.45	1	0	11	23	22	13	6	6	5
		2	4.448	84.512	44.480	26.688	12.344	4.448	8.896	0.000
6607	118.39	1	17	64	22	9	8	10	14	0
		2	208.518	117.858	13.599	13.599	9.066	4.533	4.533	4.533
6607	119.33	1	96	72	109	126	90	56	33	9
		2	32.508	102.168	130.032	130.032	116.100	55.728	32.508	9.288
6607	120.25	1	8	11	2	2	0	0	0	0
		2	97.196	128.122	26.508	8.836	4.418	0.000	0.000	0.000
6607	133.23	1	1	0	0	0	1	0	0	0
		2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6607	137.22	1	3	58	217	133	91	45	25	3
		2	8.212	143.710	316.162	176.558	90.332	86.226	36.954	16.424
6607	137.23	1	6	29	41	80	45	27	13	2
		2	66.195	61.782	105.912	52.956	26.478	30.891	8.826	13.239
6608	87.35	1	360	11	13	6	6	8	2	0
		2	877.150	162.190	122.470	33.100	39.720	26.480	6.620	3.310
6608	130.28	1	23	43	21	10	1	1	1	0
		2	29.552	51.716	18.470	0.000	0.000	0.000	0.000	0.000
6608	130.30	1	13	29	29	15	7	1	0	0
		2	47.879	66.294	22.098	11.049	11.049	7.366	0.000	0.000
6608	133.25	1	32	19	7	8	2	0	1	0
		2	151.578	79.398	21.654	25.263	7.218	0.000	0.000	0.000
6610	120.40	1	0	0	0	0	0	0	0	0
		2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6610	130.28	1	0	5	6	9	2	3	0	1
		2	0.000	7.128	10.692	0.000	0.000	0.000	0.000	0.000
6611	120.25	1	0	0	0	0	0	0	0	0
		2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6611	137.23	1	32	1	1	0	0	0	0	0
		2	127.575	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6706	83.55	1	9	17	36	53	35	33	23	25
		2	41.808	62.712	70.551	39.195	44.421	23.517	15.678	33.969
6706	110.40	1	21	6	30	57	56	52	48	58
		2	3.074	3.074	24.592	18.444	36.888	12.296	15.370	3.074
6706	120.24	1	1	0	0	4	4	1	0	0
		2	6.278	0.000	0.000	0.000	3.139	0.000	0.000	0.000
6706	120.40	1	2	4	14	31	19	26	12	7
		2	0.000	0.000	17.550	14.625	14.625	20.475	5.850	5.850
6712	107.45	1	123	106	18	10	13	1	5	0
		2	287.586	114.297	11.061	14.748	14.748	0.000	0.000	0.000
6712	120.50	1	333	23	9	11	7	6	1	0
		2	496.110	14.380	0.000	7.190	17.975	0.000	3.595	3.595

$$\tilde{s}_{1j} = \frac{\sum_{k=1}^m n_{1jk} n_{2jk}}{\sum_{k=1}^m n_{2jk}}, \quad (2)$$

where m = number of samples.

However, if the assumption of independence of e_{jk} is violated, (2) is not the least squares estimate of s_{1j} . A form of violation of the assumption which is common in plankton sampling is that the error term is proportional to $\sqrt{n_{2jk}}$. In this case the least squares estimate of s_{1j} is given by Cochran (1963) as

TABLE 2.—Catch of Pacific sardine larvae by type 1 (0.55-mm mesh) and type 2 (0.333-mm mesh) nets for each sample.

Cruise	Station	Net type	Standard length							
			2.5	3.75	4.75	5.75	6.75	7.75	8.75	9.75
6601	93.35	1	0	0	0	0	0	0	0	0
		2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6601	103.29	1	0	0	0	2	1	0	0	0
		2	0.000	3.285	3.285	0.000	0.000	0.000	3.285	0.000
6601	120.24	1	1	2	7	8	4	3	0	1
		2	0.000	3.233	16.165	6.466	12.932	0.000	0.000	0.000
6601	120.35	1	0	1	38	4	0	0	0	0
		2	0.000	3.283	42.679	0.000	0.000	0.000	0.000	0.000
6607	113.50	1	0	0	2	8	0	0	0	0
		2	0.000	0.000	4.858	4.858	0.000	0.000	0.000	0.000
6607	117.45	1	0	0	0	2	8	5	5	3
		2	0.000	0.000	0.000	13.344	8.896	8.896	17.792	13.344
6607	118.39	1	0	3	16	17	4	2	0	0
		2	0.000	0.000	31.731	18.132	0.000	0.000	0.000	0.000
6607	119.33	1	0	0	0	0	2	1	0	0
		2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6607	120.25	1	4	3	4	0	0	0	0	0
		2	13.254	8.836	17.672	0.000	0.000	0.000	0.000	0.000
6607	133.23	1	10	28	8	6	2	0	0	0
		2	43.030	51.636	12.909	21.515	8.606	0.000	4.303	4.303
6607	137.22	1	60	15	8	11	14	6	3	3
		2	147.816	24.636	24.636	32.848	12.318	4.106	8.212	8.212
6607	137.23	1	5	0	1	0	1	1	0	1
		2	0.000	4.413	0.000	0.000	0.000	0.000	0.000	0.000
6608	130.28	1	8	33	29	27	9	5	1	1
		2	36.940	70.186	33.246	33.246	3.694	7.388	3.694	0.000
6608	130.30	1	83	56	15	8	1	0	2	1
		2	99.441	77.343	7.366	11.049	7.366	0.000	3.683	0.000
6608	133.25	1	11	63	13	3	6	0	1	0
		2	43.308	198.495	14.436	10.827	3.609	0.000	0.000	0.000
6610	120.40	1	2	14	9	4	5	8	6	8
		2	0.000	10.761	7.174	3.587	14.348	17.935	10.761	3.587
6610	130.28	1	2	32	2	0	0	0	0	0
		2	7.128	46.332	0.000	0.000	0.000	0.000	0.000	0.000
6611	120.25	1	1	13	263	294	111	75	40	33
		2	3.621	28.968	318.648	152.082	83.283	83.283	65.178	32.589
6611	137.23	1	1	23	2	1	0	0	0	0
		2	10.935	54.675	0.000	0.000	0.000	0.000	0.000	0.000
6706	110.40	1	0	1	9	0	0	0	0	0
		2	0.000	0.000	3.074	0.000	0.000	0.000	0.000	0.000
6706	120.24	1	5	30	57	13	4	1	0	0
		2	113.004	194.618	116.143	12.556	0.000	0.000	0.000	0.000
6706	120.40	1	4	118	175	65	25	11	5	2
		2	32.175	216.450	187.200	35.100	8.775	5.850	2.925	0.000

$$\tilde{s}_{1j} = \frac{\sum_{k=1}^m n_{1jk}}{\sum_{k=1}^m n_{2jk}} \quad (3)$$

Plots of n_{1jk} and n_{2jk} did not clearly indicate the relation between e_{jk} and n_{2jk} . Thus both methods of estimating s_{1j} were used.

Examination of the data revealed that a linear equation is appropriate to describe the relation between s_{1j} and L_j when $L_j \leq 5.75$ mm.

$$\tilde{s}_{1j} = a + bL_j \quad (4)$$

Linear regression techniques were used to estimate the parameters, a and b , of the equation.

RESULTS

Table 1 presents catches of anchovy larvae by the type 1 and type 2 nets for each sample. The first two digits of the cruise refer to year and the second two by month. Station notation is explained by Ahlstrom (1966). Larvae greater than 9.75 mm were captured, but the numbers involved were too small to be useful for the study. Estimates by (2) and (3) of s_{1j} are as follows:

$L_j(\text{mm})$	$\tilde{s}_{1j}(2)$	$\tilde{s}_{1j}(3)$
2.50	0.312	0.367
3.75	0.512	0.603
4.75	0.711	0.699
5.75	0.946	1.057
6.75	0.875	0.916
7.75	0.753	1.021
8.75	1.007	1.226
9.75	0.664	1.087

Plots, Figure 1, of the estimates show that there is a very good linear relation between the estimates and L_j when $2.50 \text{ mm} \leq L_j \leq 5.75 \text{ mm}$.

When $L_j > 5.75 \text{ mm}$ $\tilde{s}_{1j}(2)$ decreases while $\tilde{s}_{1j}(3)$ fluctuates about 1. Thus it appears that a linear relation (4) provides an adequate de-

scription of the relation between $\tilde{s}_{1j}$ and L_j when $2.50 \text{ mm} \leq L_j \leq 5.75 \text{ mm}$. When $L_j > 5.75 \text{ mm}$

it is assumed that $\tilde{s}_{1j} = 1$. Vannucci (1968) reviewed papers that used the logistic and normal distribution functions which have s_{ij} approaching 1 as an asymptote rather than the discontinuous equation used in this study. The data used in this study are not accurate enough when $L_j > 5.75 \text{ mm}$ to warrant use of an asymptotic relation. The very good linear relation between L_j and $\tilde{s}_{1j}$ when $L_j \leq 5.75 \text{ mm}$ and the high values of $\tilde{s}_{1j}$ when $L_j = 5.75 \text{ mm}$ indicate that any deviation from the equation used in this study would cause minor errors when $\tilde{s}_{1j}$ are used to correct catches of anchovy larvae for loss through meshes.

The estimate of a from (2) and (4) is -0.1942 , b is 0.1945 , and the correlation coefficient, r , is 0.9961 . When (3) was used a is -0.1075 , b is 0.1850 , and r is 0.9814 .

Table 2 contains catches of sardine larvae used in the study. Estimates by (2) and (3) of s_{1j} are as follows:

$L_j(\text{mm})$	$\tilde{s}_{1j}(2)$	$\tilde{s}_{1j}(3)$
2.50	0.375	0.358
3.75	0.385	0.436
4.75	0.817	0.782
5.75	1.754	1.330
6.75	1.275	1.203
7.75	0.881	0.926
8.75	0.584	0.526
9.75	0.873	0.854

The estimates of s_{1j} for sardine larvae are similar to those for anchovy larvae. Thus the same discontinuous function is assumed. The estimate of a from (2) and (4) is -0.2382 , b is 0.2107 , and r is 0.9320 . Estimates obtained when (3) was used are a , -0.2286 , b , 0.2084 , and r , 0.9639 . The resulting curves for both anchovy and sardine larvae are shown in Figure 2. The curves differ little either within or between species. Since the highest value of r , 0.9961 , was estimated for anchovy larvae using equation (2), the somewhat arbitrary decision was made to use the results obtained from equation (2).

ESTIMATION OF PORTION OF LARVAE PASSED THROUGH MESHES OF TYPE 1 (0.55-MM MESH) NET

The type 1 net has been the major plankton sampler of the CalCOFI. Estimates of spawning biomass of the northern anchovy population have been based on the ratio of total catches of sardine larvae to total catches of anchovy larvae (Ahlstrom, 1968). If there are major differences in the percentages of sardine and anchovy larvae retained by the net, then the estimates of anchovy spawning biomass may be seriously in error. Ahlstrom (personal communication) believed that his assumption that the two species were sampled equally well was valid because of the similar forms of larvae of the two species and his interpretations of catch curves of larvae of the two species.

Catch (average) curves of anchovy and sardine larvae were calculated from a series of CalCOFI samples taken during the months of January through July during the decade 1951-1960. More than 10,000 samples are involved. Catch curves were calculated for day and night samples separately because of marked differences between the two. The curves were then corrected for nonretention of larvae as follows:

$$n'_{1jko} = n_{1jko}(1/s_{1j}) \quad (5)$$

where n'_{1jko} = the corrected catch of larvae of size L_j by net type 1 in the k th time of day, and oth species.

$$k = \begin{cases} 1 & \text{for night samples} \\ 2 & \text{for day samples} \end{cases}$$

$$o = \begin{cases} 1 & \text{for anchovy} \\ 2 & \text{for sardine} \end{cases}$$

The corrected and uncorrected curves plotted on a semilogarithmic scale are shown with n_{1jko} and n'_{1jko} expressed in percent of total in Figures 3-6. The corrected curve for anchovy larvae caught at night shows a slight increase in the rate of decline with size. The corrected curve for anchovy caught during the day is essentially linear as is the corrected catch curve for sardine larvae caught during the night. The corrected catch curve for sardine larvae caught during the day shows a decreasing rate of decline with size. In all cases the corrected curves show little indication of undersampling of small larvae.

The following equation was used to estimate the portion of larvae not collected by the type 1 net because of passage through the mesh:

$$P_{1o} = \frac{\sum_{jk} \sum n_{1jko}}{\sum_{jk} \sum n'_{1jko}} \quad (6)$$

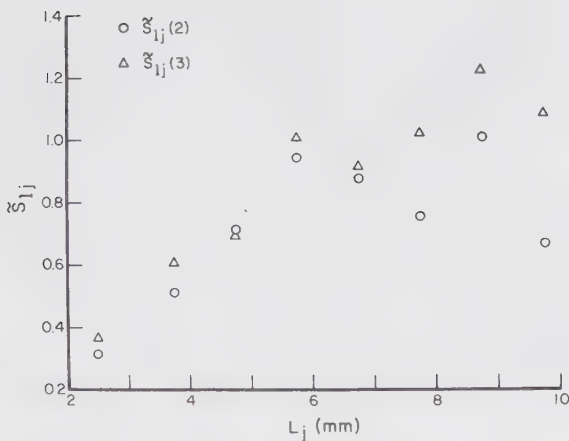


FIGURE 1.—Scatter diagram of estimates of mesh retention by type 1 (0.55-mm mesh) net using equation (2) ($s_{1j}(2)$), mesh retention using equation (3) ($s_{1j}(3)$), and standard length (L_j) for northern anchovy larvae.

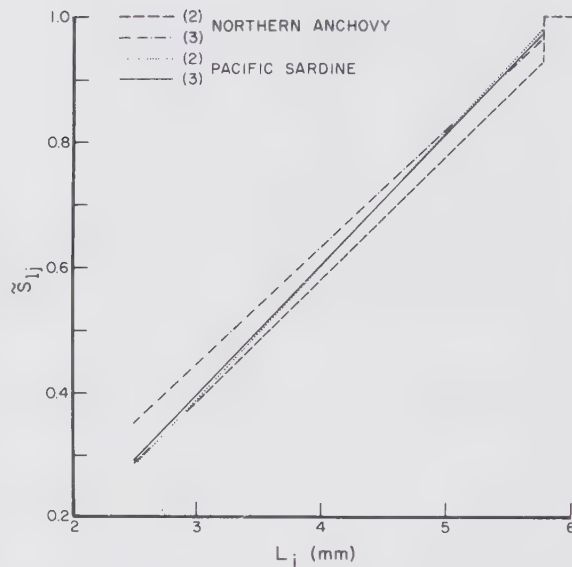


FIGURE 2.—Estimates of mesh retention by type 1 (0.55-mm mesh) net (s_{1j}) against standard length (L_j) for larvae of northern anchovy and Pacific sardine using equations (2) and (3).

where $1 - P_{1o}$ = portion of larvae of species o not sampled by type i net because of passage through meshes.

Equation (6) implies that an equal number of night and day samples are taken. This is approximately correct. The estimate of P_{1o} for anchovy is 0.60. The estimate of P_{1o} for sardine is 0.67. Thus anchovy larvae are undersampled by about 12% relative to sardine larvae because of differences in mesh retention and size composition.

CATCH CURVE OF TYPE 3 (0.505-MM MESH) NET

Figure 7 shows the catch curve plotted on a semilogarithmic scale of anchovy larvae caught by the type 3 net during 1969 by the CalCOFI. This data is preliminary (P. E. Smith, personal communication) and catches have not been separated by day and night. The interesting feature of this curve is that it is essentially linear

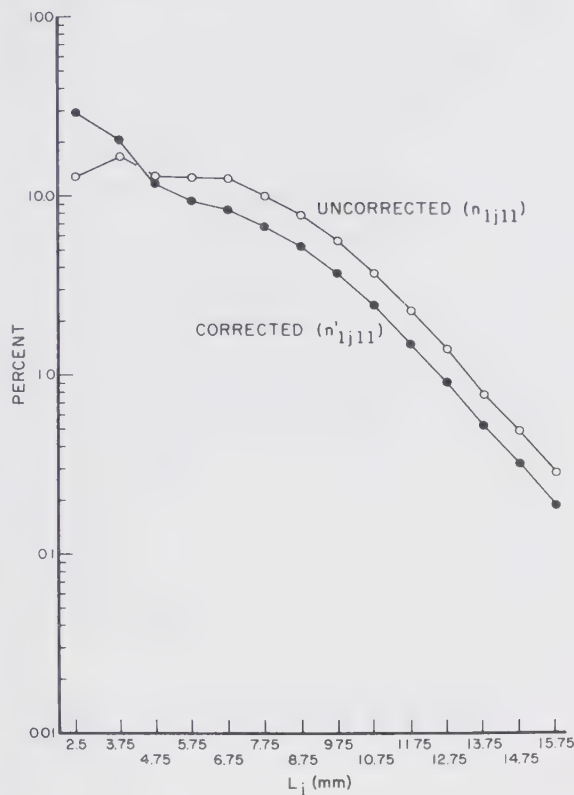


FIGURE 3.—Corrected (n'_{1j11}) and uncorrected (n_{1j11}) catches by standard length (L_j) of northern anchovy taken at night with type 1 (0.55-mm mesh) net. Catches are expressed in percent of total.

with size. This indicates that few if any small anchovy larvae escape capture by passing through the meshes. Thus a 10% decrease in mesh size and a large decrease in the variance of mesh size changed P_{11} from 0.60 to about 1. The difference in P_{11} between the type 1 and type 3 nets means that total catches of anchovy larvae by the type 1 net should be multiplied by 1.7 to be comparable to catches of anchovy larvae by the type 3 net.

DISCUSSION

The similarity of the catch curves of anchovy larvae caught by the type 3 net and the corrected catch curve for the type 1 net suggests that the estimates of s_{1j} are reasonably accurate. It

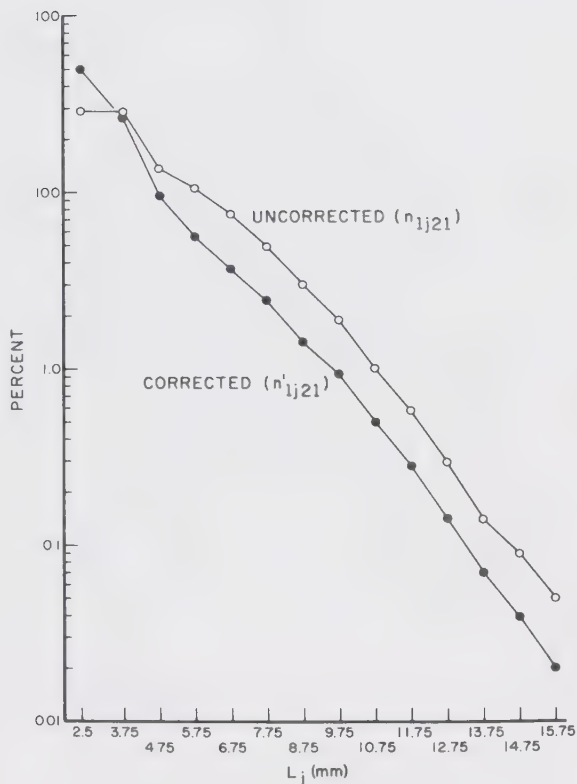


FIGURE 4.—Corrected (n'_{1j21}) and uncorrected (n_{1j21}) catches by standard length (L_j) of northern anchovy taken during day with type 1 (0.55-mm mesh) net. Catches are expressed in percent of total.

would be a remarkable coincidence otherwise as the data are independent.

It is interesting that the type 3 (0.505-mm mesh width) net apparently retains most if not all anchovy larvae, for the body depth at the insertion of the pectoral fin of 3.75-mm anchovy larvae is about 0.35 mm (P. E. Smith, personal communication) which is considerably less than the mesh width. Smith, Counts, and Clutter (1968) summarized the results of Saville (1958) by concluding that an organism must be wider than the mesh diagonal to be completely retained. A conclusion of this study is that the "diagonal rule" is too conservative for slowly towed nylon nets. Heron (1968) concluded that mesh variability is a very important factor in-

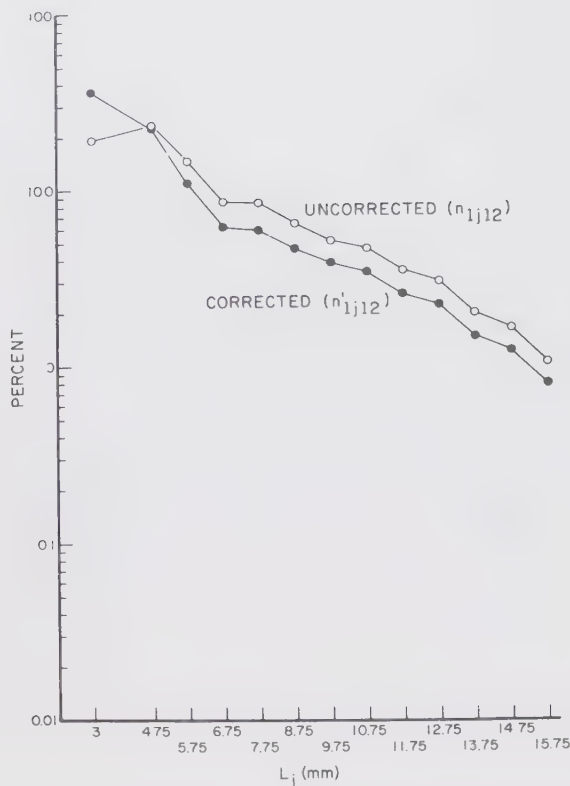


FIGURE 5.—Corrected (n'_{1j12}) and uncorrected (n_{1j12}) catches by standard length (L_j) of Pacific sardine taken at night with type 1 (0.55-mm mesh) net. Catches are expressed in percent of total.

fluencing escapement and implied that the coefficient of variation of mesh width is greater for silk than nylon nets. The results of this study agree with Heron's conclusions.

The results indicate that two similar types of sampling gear have greatly different mesh retention properties for anchovy larvae. This implies that considerable care should be taken in the selection of sampling gear if quantitative estimates of the abundance of fish larvae are desired. The similarity in mesh retention shown for anchovy and sardine larvae may be due to the fact that the larval forms are very similar. However the diversity of forms found in fish larvae is tremendous. Mesh retention should be estimated before quantitative estimates of the relative

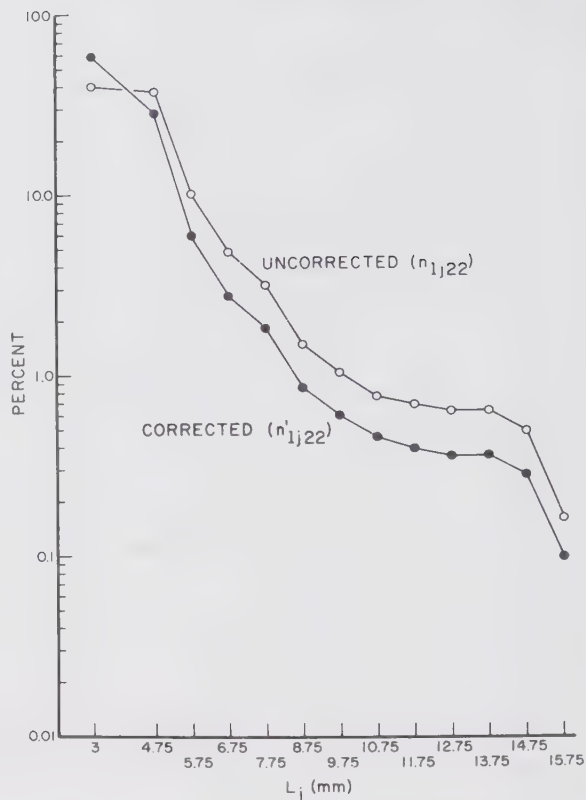


FIGURE 6.—Corrected (n'_{1j22}) and uncorrected (n_{1j22}) catches by standard length (L_j) of northern anchovy taken during day with type 1 (0.55-mm mesh) net. Catches are expressed in percent of total.

abundance of larvae of different species of fish are attempted. The results indicate that adequate estimates of mesh retention can be made from less than 30 samples containing the desired species of fish larvae. If the mesh retention curve is curvilinear in the region of fish larvae of minimum size, more samples may be necessary.

The reasoning of Hjort (1926) in expecting a critical period in the early life of fish larvae is intuitively pleasing. Hunter (1972) showed experimentally that a much higher density of food organisms is necessary for survival of 4- to 6-mm anchovy than for larger larvae. However, there is no indication of a critical period at the 4- to 6-mm sizes in this study, i.e., there are no major

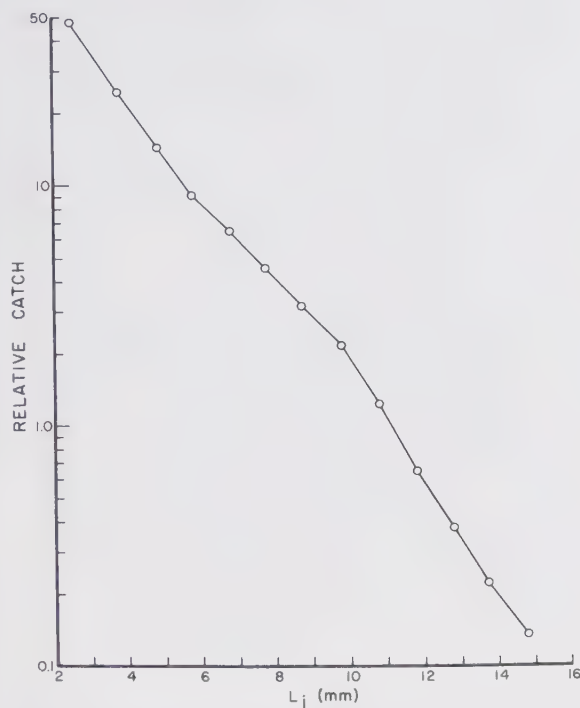


FIGURE 7.—Catches of northern anchovy by standard length (L_j) taken by type 3 (0.505-mm mesh) net.

changes in the slopes of the catch curves. However, since the catches are plotted with size rather than age, a faster rate of growth at small sizes relative to large sizes could cause small size larvae to be relatively undersampled. If this were the case, a critical period could occur but not be indicated by catches plotted with size. Kramer and Zweifel (1970) indicated that the growth rate of anchovy larvae increases rather than decreases with size during the first few millimeters of growth. Another factor that could influence the catch rate of larvae differently with size is avoidance of the net. However, experience indicates that avoidance increases with size (Lenarz, in press). Thus, the large larvae should be relatively undersampled. I conclude, therefore, that available data does not provide any evidence of the critical period for sardine or anchovy larvae. This conclusion is

in agreement with other authors that have examined catch curves of fish larvae, e.g., Marr (1956).

ACKNOWLEDGMENTS

I owe considerable thanks to Drs. Paul E. Smith and Elbert H. Ahlstrom for encouraging this study and for providing many constructive comments. Thanks are also due to Sharron G. Cramer, Biological Aid, for processing many of the samples and for her comments on the technique of measuring fish larvae, and to Bradley W. Cowell, NOAA Jr. Fellow, for performing many of the calculations.

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GROWTH HORMONE- AND PROLACTIN-LIKE PROTEINS OF THE BLUE SHARK (*PRIONACE GLAUCA*)

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ABSTRACT

The two major disc-electrophoretic components, designated as "slow" and "fast," which are seen in fresh homogenates of the pars distalis of the blue shark (*Prionace glauca*) pituitary gland were isolated. Some alteration of the proteins occurred during the purification as evidenced by appearance of a slightly faster migrating band in each. The slow component and its altered form had a molecular weight of 22,000 daltons; the fast, and its modified form, 20,000 daltons. The two proteins were very similar chemically and immunologically, but definite differences were noted. Both gave a precipitin line with antiserum to mouse growth hormone, although quantitatively different, but neither reacted to antiserum to mouse prolactin. The peptide maps of the two proteins were identical except for three peptides. Both contained two moles of tryptophan and six half-cystine residues. These results indicate that the pars distalis of the blue shark contains two very similar proteins that resemble both growth hormone and prolactin of mammals.

There have been few reports that have dealt with the isolation of purified preparations of growth hormone and prolactin from pituitary glands of fish. This most probably stems from the fact that there is no convenient bioassay for these piscine hormones. Wilhelmi (1955) purified growth hormone from the hake; Donaldson, Yamazaki, and Clarke (1968) reported on prolactin of salmon; and Emmart and Bates (1968) described purification of prolactin of the pollack. As a means of circumventing bioassays, we thought that disc electrophoresis might prove successful. The method has been used by us to follow the purification of growth hormone and prolactin of the mouse (Cheever, Seavey, and Lewis, 1969), human (Lewis, Singh, and Seavey, 1971), and turtle (Singh, Seavey, and Lewis, 1972).⁴ The approach appeared even more rea-

sonable for the isolation of the shark hormones when we found that the electrophoretic pattern of the pars distalis extract contained only two major bands. This has been found to be the case for many species, and growth hormone usually has been identified as the slower migrating of the two bands (Nagy, Kurz, and Baranyai, 1969; Nicoll and Nichols, 1971; Nicoll and Licht, 1971). An exception to this has been found in the human (Friesen, Guyda, and Hardy, 1970; Lewis et al., 1971) where growth hormone is more acidic than prolactin and, therefore, migrates more rapidly during electrophoresis at an alkaline pH.

Making the assumption, then, that the two major bands seen in the electrophoretic pattern of the shark pituitary extract were growth hormone and prolactin, we devised a procedure for their isolation and used electrophoresis as a means of following the purification. The isolation procedure and some properties of the purified proteins are described in this communication.

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⁴ Singh, R. N. P., B. K. Seavey, and U. J. Lewis. 1972. Purification and some properties of growth hormone and prolactin of the turtle. (Manuscr.)

MATERIALS AND METHODS

DISC ELECTROPHORESIS

Our use of the method has been described (Lewis, Litteria, and Cheever, 1969). For routine analytical analyses the gel was made of 7.5% acrylamide and 0.25% N-N'-methylenebisacrylamide. For quantitation of the amount of protein in a stained band, ethylene diacrylate was substituted for the cross linking agent.

MOLECULAR WEIGHT

Molecular weights were estimated by using disc electrophoresis (Cheever and Lewis, 1969).

PEPTIDE MAPPING AND AMINO ACID ANALYSES

Our procedure for peptide mapping has been described (Seavey and Lewis, 1971). Total amino acid analyses were done on performic acid oxidized samples by means of automated analysis. Tryptophan was determined by the method of Beaven and Holiday (1952).

IMMUNODIFFUSION

Mouse growth hormone prepared by the method of Cheever et al. (1969) was used for immunization of monkeys; antiserum to mouse prolactin was produced in rabbits by using hormone prepared as described in the same publication. The antiserum to mouse growth hormone was not contaminated with antibodies to mouse serum proteins or mouse prolactin; the antiserum to mouse prolactin, likewise, did not give a precipitin line with serum proteins nor did it cross react with mouse growth hormone. Immunodiffusion was carried out by the method of Ouchterlony.

COLLECTION AND STORAGE OF GLANDS

The pars distalis was removed within 30 min after the animals were killed and immediately homogenized in water (5 ml/g wet tissue) at 5°C. The homogenate was stored at -20°C until it could be fractionated. This procedure was

used to minimize alteration of the proteins, as judged by electrophoretic analysis. More rapid changes occurred when the glands were stored intact.

ISOLATION PROCEDURE

All processes were carried out at 5°C. The pars distalis (7.6 g wet weight) from 87 blue sharks were homogenized in 38 ml water. The pH of the homogenate was adjusted to 10 with dilute NaOH and made 10^{-3} M in diisopropylphosphofluoridate. After 4 hr of stirring the homogenate was centrifuged at $20,000 \times g$ for 40 min. The supernatant fluid was decanted, its pH lowered to 8 with dilute HCl and set aside. The insoluble residue was suspended in 0.05 M $\text{Na}_2\text{CO}_3\text{-NaHCO}_3$ buffer, pH 10 (2.5 ml/g original tissue) and stirred for 16 hr. After centrifugation, the supernatant fluid was pooled with the first extract and the pH of the mixture adjusted to 8. The insoluble tissue was discarded when electrophoresis showed that all the desired components had been extracted.

The crude extract was concentrated to about 15 ml on a Diaflo UM-10 membrane⁵ (Amicon, Lexington, Mass.) and placed on a column of Sephadex G-150, 5×90 cm and developed with 0.01 M NH_4HCO_3 . Every fifth tube was analyzed by disc electrophoresis (100 μ liter aliquots) and the tubes that contained the two proteins that were assumed to be growth hormone and prolactin were combined and concentrated to about 10 ml on a UM-10 Diaflo membrane. Figure 1 shows the elution pattern of the Sephadex column; the stippled area contained the desired components, S and F.

The concentrated solution from the Sephadex chromatography was applied to a column of DEAE-cellulose (Whatman 32) with dimensions of 0.9×10 cm and which had been equilibrated with 0.01 M NH_4HCO_3 . The flow rate was 38 ml/hr. Once the sample had been applied, the column was washed with 25 ml of 0.01 M NH_4HCO_3 . No appreciable amount of protein

⁵ Reference to trade names in this publication does not imply endorsement of commercial products by the National Marine Fisheries Service.

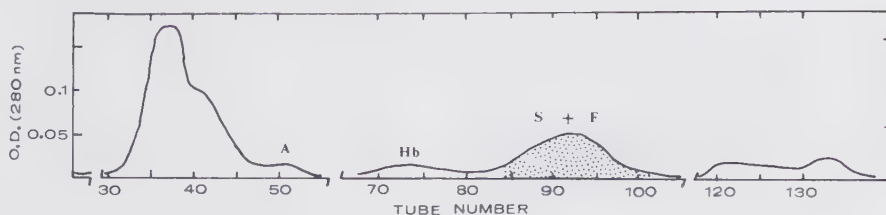


FIGURE 1.—Elution pattern obtained by chromatography of an alkaline extract of the pars distalis on Sephadex G-150. Each tube had a volume of 14 ml. The slow and fast electrophoretic components (S and F) were found in the stippled area. A = albumin; Hb = hemoglobin.

was eluted by the process. A gradient was next begun and was made by mixing equal portions (100 ml each) of 0.01 M and 0.1 M NH_4HCO_3 . This eluted a major peak. A second gradient of equal volumes (150 ml each) of 0.1 M and 0.2 M NH_4HCO_3 was begun immediately. This gradient eluted a second peak. The results obtained with the DEAE-cellulose chromatography are shown in Figure 2.

The two major peaks eluted during chromatography on DEAE-cellulose were lyophilized. The yield of component F was 43 mg; that of component S, 22 mg.

RESULTS

ELECTROPHORETIC ANALYSES

Pituitary Extracts

The water homogenate of the pars distalis showed two principal electrophoretic components when analyzed within 30 min after the sharks were taken from the sea. An alkaline extract of the glands, made about a week later, gave an almost identical pattern except that a definite band could be seen just ahead of each of the major components S and F. This is shown in Figure 3. The S and F components were assumed to be growth hormone and prolactin, respectively, and were the components for which we devised an isolation procedure. The bands designated as A, B, and C were minor components seen in both the water homogenate and the alkaline extract. A fast component also migrated near the buffer front.

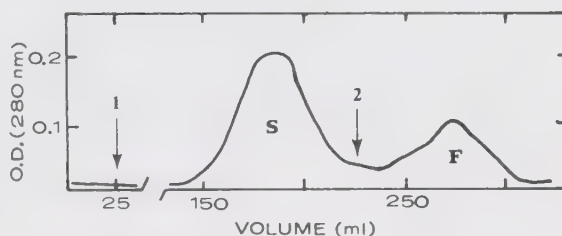


FIGURE 2.—Elution pattern obtained by chromatography of the S + F fraction of Figure 1 on DEAE-cellulose. The first gradient was begun at 1 and a second at 2. The S and F components were resolved as indicated in the drawing.

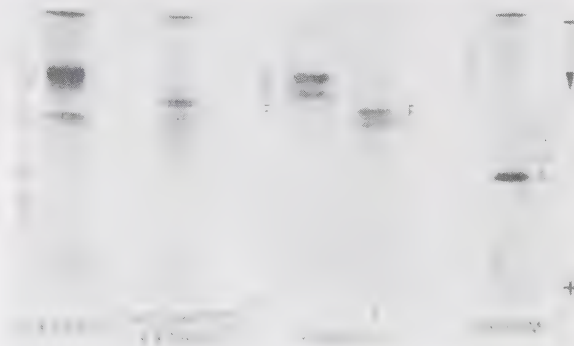


FIGURE 3.—Electrophoretic patterns (pH 9.5) of various shark materials. The pattern for the incubated sample was obtained after heating the alkaline extract at 37°C for 2 hr. S and F are the slow and fast components; S' and F' are the bands that formed during isolation of the proteins. Components A through E are discussed in the text. A thread marks the original buffer front (bromphenol blue) in two of the gels.

The conversion of the S and F bands to more rapidly migrating components became more pronounced as the fractionation of the extract progressed. As seen in Figure 3, by the time the proteins were isolated, each was a definite doublet. The new components are designated as S' and F'. The same type of alteration of the S and F proteins occurred even during storage of intact glands at -20°C . After one month, the S' and F' were of about equal intensity to that of the original S and F bands. The alteration was barely noticeable however in a water homogenate of glands stored for the same length of time at -20°C . We determined also how incubation at 37°C affected the conversion of components S and F. After 2 hr at that temperature, S and F had virtually disappeared and a new band intermediate in mobility between S and F was present. This is shown in Figure 3. All bands disappeared if the extract was left at 37°C for 6 hr.

Serum

To determine whether either S or F might be serum components we analyzed a sample of shark serum (Figure 3). There was a faint band (E) in the region of S but none for F in gels of 7.5% acrylamide. At 10% and 12% acrylamide band E was more retarded than S, however. Component A of the pituitary extract lined up with the major component of serum in four concentrations of acrylamide.

PURIFICATION

The elution pattern obtained from chromatography of the alkaline extract on Sephadex G-150 is shown in Figure 1. As described in the experimental section above, the S and F components were located by disc electrophoresis and both were found in the same elution peak (stippled area). The peak of high molecular weight material at the beginning of the elution pattern gave an abnormally high optical density reading because of opalescence. The peak designated as A had the same electrophoretic pro-

perties of band A of Figure 3 and, as indicated above, was presumed to be albumin. The peak eluted just before S and F was labeled Hb (hemoglobin) because of its red color. Electrophoretically the material gave two very diffuse bands.

Figure 2 shows the elution pattern obtained by chromatography of Sephadex peak S + F on DEAE-cellulose. No protein was eluted with 0.01 M NH_4HCO_3 . The first major peak, found to be F by electrophoretic analysis, was eluted by gradient 1 (0.01 M to 0.1 M NH_4HCO_3). A second gradient (0.1 M to 0.2 M NH_4HCO_3) eluted a second peak which was found to be component F by electrophoresis. The shoulder on the leading edge of peak F was probably a result of a small, rapid increase in ionic strength when the second gradient began.

The material of peaks S and F were lyophilized. The yield of S was 43 mg and 23 mg for F. Figure 3 shows the electrophoretic pattern of each of these samples. That each was a doublet was a result of alteration that took place during isolation. The conversion became progressively more pronounced during the purification.

MOLECULAR WEIGHTS

The molecular weights of components S and F as seen in electrophoretic patterns of the alkaline extract were $S = 22,000$ and $F = 20,000$. Identical values were obtained when the purified S and F fractions were analyzed. Likewise S' and F' had molecular weights indistinguishable from the corresponding S or F form although the molecular weight determination is accurate only to $\pm 2,000$. The $\log R_m$ vs. gel concentration curves for these components are shown in Figure 4. Of significance was the fact that there was a greater charge difference between S and S' than between F and F'. This is additional evidence that S and F are different substances. The slopes of the curves of Figure 4 were converted to molecular weight values by reference to a standard curve constructed from proteins of known molecular weight (Cheever and Lewis, 1969).

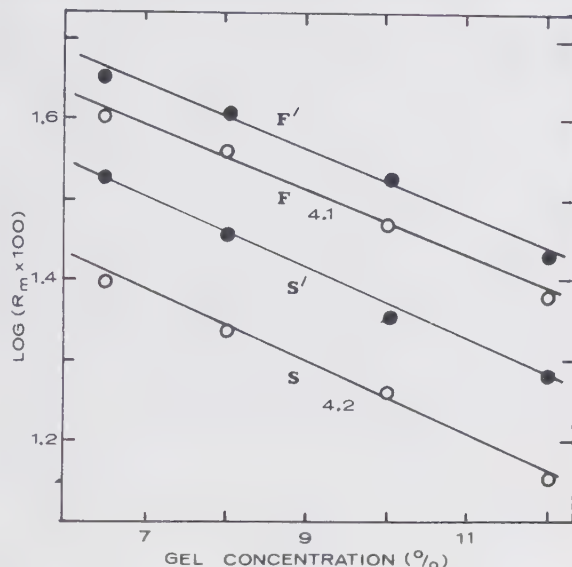


FIGURE 4.—A Ferguson plot of the relative mobility (R_m) of the S and F components and their altered forms (S' and F') versus the concentration of acrylamide used for the gel-electrophoresis.

The molecular weights of the other electrophoretic components seen in Figure 3 were A = 68,000; B = 65,000; C = 60,000; D = 47,000; E = 71,000; G = 64,000; H = 72,000.

IMMUNODIFFUSION

The purified preparations of S and F, which also contained S' and F', respectively, produced a precipitin line when tested against antiserum to mouse growth hormone (Figure 5). When tested at the same concentration, S gave a more pronounced line than did F. Neither preparation gave a precipitin line with antiserum to mouse prolactin.

AMINO ACID COMPOSITION

Table 1 gives the amino acid analyses of components S and F. The composition of the two proteins was quite similar but there were definite differences and component S had a greater total number of amino acids. Both contained six half-cystines and two tryptophans.

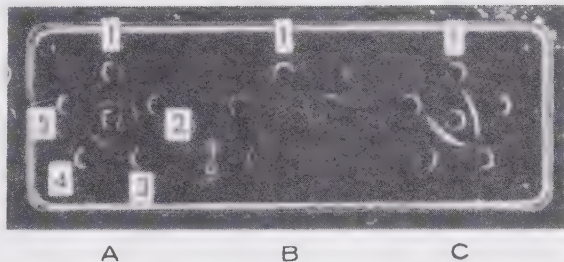


FIGURE 5.—Immunodiffusion plate for the S and F proteins. Antiserum to mouse growth hormone (10 μ liter) was in the center well of A and B; antiserum to mouse prolactin was in the center well of C. The outer wells of A contained: 1, 10 μ g component S; 2 and 5, 5 μ g mouse growth hormone; 3, 5 μ g component S; 5, 2 μ g component F. The outer wells of C contained: 1, 10 μ g component S; 2, 5 μ g mouse prolactin; 3, 10 μ g component F; 4, 5 μ g mouse prolactin. The picture was taken after 24 hr at room temperature.

TABLE 1.—Amino acid composition of performic acid oxidized components S and F.

Amino acid	Component S residues ¹	Component F residues ¹
Cysteic acid	6.0	6.0
Aspartic acid	22.6	21.7
Methionine sulfone	4.8	4.0
Threonine	10.3	8.0
Serine	19.7	13.1
Glutamic acid	31.2	31.5
Proline	10.6	7.4
Glycine	10.2	8.4
Alanine	15.7	10.3
Valine	9.0	5.6
Isoleucine	6.3	6.9
Leucine	25.8	20.6
Tyrosine	6.9	3.8
Phenylalanine	10.1	7.2
Histidine	6.5	4.7
Lysine	17.5	15.0
Arginine	14.0	7.5
Tryptophan ²	2.1	2.1

¹ Based on 22,000 daltons for S and 20,000 for F.

² Spectrophotometric (Beaven and Holiday, 1952).

PEPTIDE MAPS

Figure 6 is a drawing of the peptide map obtained with component S. The F component gave an almost identical map but was different in that peptides labeled S were not seen and another peptide labeled F was noted.

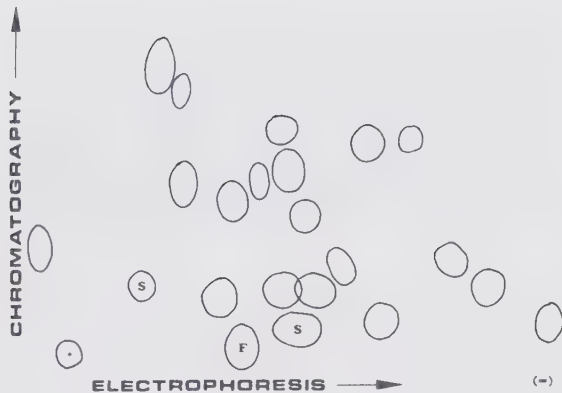


FIGURE 6.—Peptide map of a tryptic digest of component S. Chromatography was done with n-butanol-acetic-acid-water (4:1:5); electrophoresis was at pH 3.6 in a pyridine-acetic acid-water buffer (1:10:289). The peptide map of component F was identical except that peptides designated S were not seen and the peptide F was present.

DISCUSSION

From the immunodiffusion data we know that the S and F proteins are related to mammalian growth hormone. Their molecular weights also were near the values found for mammalian growth hormone and prolactin. One other observation which will be reported in detail later (Seavey et al., 1972)^{*} was that the amino acid compositions of the tryptic peptides of the peptide maps closely resembled those of bovine growth hormone (Seavey et al., 1971). But because there were six half-cystine residues in both S and F and because each contained two residues of tryptophan, these two shark proteins are more like mammalian prolactins than the growth hormones which have only four half-cystines and one residue of tryptophan. Therefore, the proteins are not only very similar to each other, but are immunologically related to growth hormone and have structural resemblances to both growth hormone and prolactin. These results support the view that growth hormone and prolactin may have developed from a common ancestral

protein. In the blue shark they appear as separate but yet quite similar substances with similarities to both growth hormone and prolactin. It will be interesting to see if there are two such proteins in the pituitary gland of cyclostomes.

If not already clear we would like to stress the point that no biological activities have been determined for the S and F components. Our assignment of growth hormone-like and prolactin-like properties are based on immunological and structural data alone. How these two components are related to the biological activities that have been reported for the shark pituitary gland is not known. Extensive biological studies are now needed to characterize these proteins. Also, more study will be given to the altered forms of the substances, and in particular the modification that was produced by incubation at 37°C. This type of study will be given to the altered forms of the hormones because of the rapid alterations that occurred even in the intact pituitary of the shark. We have observed that the prolactin activity of human growth hormone is increased when a hexapeptide is removed from the hormone by an enzyme present in pituitary extracts (Lewis et al., 1971). Biological activity of the shark hormones may also be affected by such changes. The nature of the alteration that occurs in the shark proteins is not known, but from our experiences with mammalian hormones we suspect that it is a result of deamidation, enzymic action, or a combination of both. The ease with which the shark's S and F components are converted to more acidic forms, however, strongly suggests deamidation, and the unusually large number of glutamic acid residues may actually be glutamines which rapidly lose ammonia.

ACKNOWLEDGMENTS

Much of this work was made possible by a grant from the National Institutes of Health (AM-09537). We also gratefully acknowledge the support given the project by the National Science Foundation in making the facilities of the RV *Alpha Helix* available for a 5-day cruise to study the pituitary of the blue shark. We are indebted to Dr. Y. N. Sinha of the Division

^{*} Seavey, B. K., R. N. P. Sigh, U. J. Lewis, and R. Lasker. 1972. Tentative structure for a growth hormone-like, prolactin-like protein of the shark.

of Endocrinology, Scripps Clinic and Research Foundation, for the antisera used in these studies, and to Ronald Dotson and John LaGrange of the National Marine Fisheries Service for their assistance in catching the sharks.

ADDENDUM

The S component of the shark pituitary gland was tested for its ability to produce growth in hypophysectomized *Fundulus heteroclitus*. The results are shown in Figure 7. The preparation was found to be as potent as a previously assayed sample of hake growth hormone (Wilhelmi, 1955).

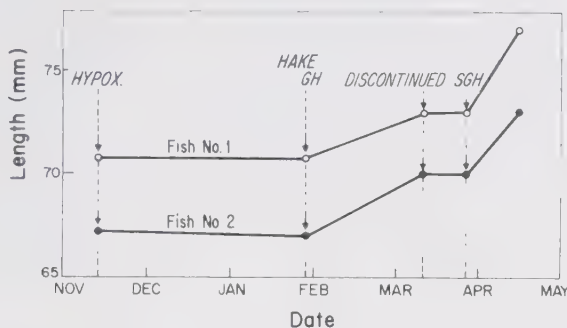


FIGURE 7.—Growth of two hypophysectomized male *Fundulus heteroclitus* after administration of growth hormone. Eleven weeks after hypophysectomy (HYPOX), injections of hake growth hormone (HAKE GH) (Wilhelmi, 1955) were begun and continued for five weeks. The injections were discontinued for two weeks and then resumed with shark growth hormone (SGH) for a period of four weeks. The S component of the shark pituitary gland was used. Both the hake and shark growth hormones were injected three times weekly at a dosage of 20 μ g of hormone per gram (wet weight) of fish.

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The instability of ocean populations

Large-scale fluctuations occur naturally in marine populations; sustained and widespread monitoring over years, even decades, will be necessary to detect the biological effects of pollution in the open ocean

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Two pitfalls await the student of man's influence on life in the oceans: first, to consider any such effects in the open ocean as inherently improbable because of the ocean's vastness or, secondly, to regard populations of marine organisms as inherently stable and to assume that any changes in them reflect the effects of man and his technology. Man's chemical invasion of the ocean does, we believe, pose a real and serious threat to marine life, despite the great volume of the oceans, despite their chemical buffering systems, and despite the probable elasticity of their complex food webs. Research on such effects must be pressed forward urgently, but unsubstantiated statements should not be made concerning "eco-catastrophes". We must remember the fable and make sure that the wolf does not make a meal of us later on.

Fishery biologists long ago discovered that the biggest problem in monitoring man's effects on life in the ocean is to separate these effects from those induced by natural climatic changes in the physical environment. We want to draw attention to the magnitude and ubiquity of natural changes in marine populations which seem, on the time-scales we can measure, to be the rule rather than the exception. Our examples tend to be drawn from fisheries data or from the data of biological monitoring programmes designed to support fishery research, because these provide almost the only source of data that have been taken in a sustained way over several decades.

The effects of climatic changes or trends may be manifest in biological trends continuing over many years, or as drastic population explosions or collapses. The classical case of a population collapse is that of the tilefish, a deepwater species discovered near the edge of the continental shelf off the east coast of the United States in 1879. A fishery developed quickly, but within three years the stock met with disaster. In March and April of 1883 vessel after vessel reported sighting dead tilefish floating on the surface, and exploratory fishing soon afterwards did not yield a single fish of this species in its normal habitat, but by 1898 the stocks were again abundant enough to support a fishery. This destruction was apparently caused by a temporary flooding of the continental edge by abnormally cold deep water.

Events of this nature may be caused by temporary instabilities in ocean systems in which longer-term trends cannot be demonstrated. Such, for instance, are "El Ninos" that occur in the eastern boundary currents in both Atlantic and Pacific oceans. The name "El Nino" (the child) originates from Peru where this phenomenon occurs around Christmas time. El Nino, associated with a slackening of the normal trade winds, is heralded by a reduction in the intensity of the normal

coastal upwelling, and an incursion of tropical surface water. Off Peru, El Nino causes dramatic changes in the availability of anchovies to fishermen and to fish-eating birds, because these cold-water fish stay deeper than normal, and the guano birds are unable to dive deep enough to feed effectively. The population of 28 million birds (about 80 per cent guanay cormorant and 20 per cent brown pelican) crashed during the 1957-59 period to a little over 5 million; from a recovery by the mid-1960s to 16-18 million, they again crashed in the 1966 El Nino to about 4 million, and were slowly recovering again until the current 1972 El Nino, to which the population is again responding. Marine climatic data for the Pacific Ocean demonstrate that this must have occurred on at least 10-12 occasions during the present century, and one can infer that the catastrophic deaths of sea-birds off Peru are one manifestation of major, ocean-wide anomalies in atmospheric circulation.

However, although data on the ocean climate of the eastern Pacific does not indicate any sustained trends, such can be found in biological data taken by the CalCOFI (California Cooperative Oceanic Fisheries Investigations) programme, although these are restricted to fish populations affected by fishing operations, and are not mirrored in other biological or in the climatic data. Over the years from 1940 to the present, the population of anchovy (*Eugraulis mordax*) has greatly increased, while those of sardines (*Sardinops coerulea*) and mackerel (*Scomber japonicus*) have dwindled almost to extinction; the decline of the latter two species due to the stress of overfishing and to the failure of young fish to survive in several years of anomalous climate in the 1950s may have sustained the five-fold increase in the anchovy population. Even within the highly urbanised and smog-ridden Los Angeles bight, where very heavy pollution by crude oil spills and leaks, by pesticides and heavy metals have been well documented, the anchovy population shows the same increase as elsewhere off California and the amount of zooplankton still varies from year to year within the same limits as two decades ago (Figure 1).

Further to the north, routine observations have been made for many years at Ocean Weather Station "Papa" to monitor biological changes in the north-east Pacific Ocean. An example of the data derived from Station "Papa" is that for zooplankton biomass in standard 0-150 m vertical hauls; within the 12-year sampling period there are three distinct periods (see Figure 2). The factors causing the anomalously low biomass in 1962-1964 have not yet been identified, but in the absence of any long-term change in the total crop of zooplankton in the north temperate mid-Pacific Ocean, the observed fluctuations in

zooplankton standing stock can be reasonably supposed to result from environmental effects. In fact, the variations in biomass have been related to surface salinities, which may be a measure of vertical mixing in the area—a process dependent on the shifting Aleutian atmospheric low pressure cell. This shift could also explain the major sea surface anomalies in temperature which characterise this part of the ocean.

Herrings and herring-like fishes undergo considerable natural fluctuations in population size and because of their great importance in mediaeval economies there is at least qualitative information about their changes in abundance extending back for several hundred years in some instances. One such fishery is found around Japan. From the earliest days it has been a multi-species fishery based upon a sardine (*Sardinops melanosticta*), and an anchovy (*Engraulis japonicus*) together with some round-herring (*Etrumeus micropus*). The fishery reached a peak of more than 1.1 million tons in the 1930s, but has since declined to about half this figure. In the 1930s sardines accounted for the bulk of the catch but the *Sardinops* stock then started to decline and with it the fishery. Similar fluctuations in this fishery have been recorded in the half-millennium since it was founded about the year 1500. In fact, the present decline is the third one to be recorded during this period.

A major sardine population off Japan apparently occurs only when "warm" oceanographic conditions obtain, that is, when the influence of the warm Kuroshio water is greatest around the Japanese islands; relatively "good and poor" decades in the past

half-century are correlated with warm and cool oceanographic conditions. Although over-exploitation of the entire oriental sardine stock has been put forward as the sole cause of the decline, the failure to recruit young fish to the stock in the years 1938-41 as a result of environmental changes seems more likely. In the late 1930s the pattern of currents changed to such an extent around Japan that the migration patterns of the sardines were modified and spawning occurred in areas where the young fish would be vulnerable to the effects of winter cooling. The changed location of the present centres of the sardine population tend to confirm the effect of environmental, rather than fishery, changes.

Failures to recruit young fish because of anomalous environmental conditions have been demonstrated for at least three other species of sardines: the Californian *Sardinops caerulea* mentioned already; the South African *Sardinops ocellata*; and the Ghanaian *Sardinella aurita*. In the Californian and South African examples, perhaps because combined with altered parent stock age-compositions due to fishing pressure, such events appear to have initiated major downward population trends.

The major biological fluctuations discussed so far have been mostly "either-or" situations in which the phase-change occurs relatively rapidly. Rather different are the events of this century in the high latitudes of the North Atlantic, in which a general warming trend in the surface waters, associated with changes in the atmospheric circulation pattern, lasted for approximately 30 years from the early 1920s. Cod (whose northward distribution is limited by an inability to survive in water colder than 2°C) began to appear, by migration from the Icelandic stocks, on the coast of Greenland for the first time in living memory in 1917. By 1960 they had built up a population sustaining a fishery yielding more than 400 000 tons each year, but a reversion to the climatic conditions of the first decades of this century will, presumably, result in the disappearance again of the Greenland stock, and the collapse of this great fishery.

Long-term trends in high-latitude Atlantic plankton have also been observed in samples that have been collected from a substantial area of the North Atlantic at monthly intervals for the last 23 years, using automatic samplers towed from merchant ships and ocean weather ships. There are two major patterns in the data, first, a roughly linear downward trend which is still continuous and, second, a more complex trend with peaks in the early fifties and late sixties and a period of low abundance between (see Figure 3). The influences producing these trends have not yet been identified but there are indications, based on geographical and species relationships, that they are produced by climatic changes acting either directly on the plankton populations, or indirectly through induced changes in the strength and direction of ocean currents.

Similarly, in the western English Channel off Plymouth notable changes in the quality of the water have occurred, as indicated by a

Figure 1 Fluctuations in the amount of zooplankton and anchovy eggs in the polluted Los Angeles Bight show the same increase in the anchovy population as seen elsewhere off the Californian coast

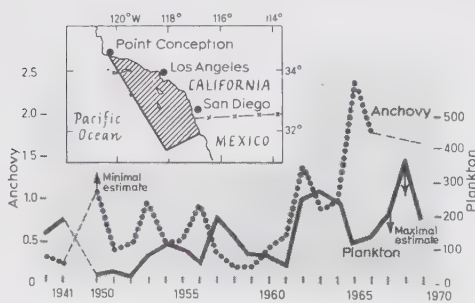
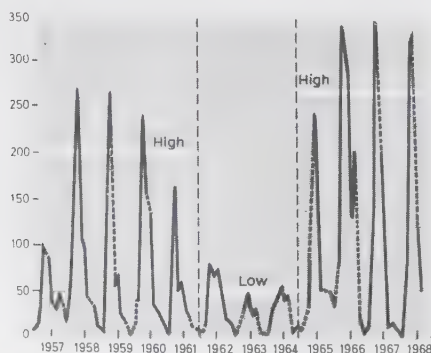


Figure 2 Records of zooplankton biomass sampled at a single ocean station show three distinct phases. The cause of the trough has not been explained, but in view of the recovery natural causes were probably responsible



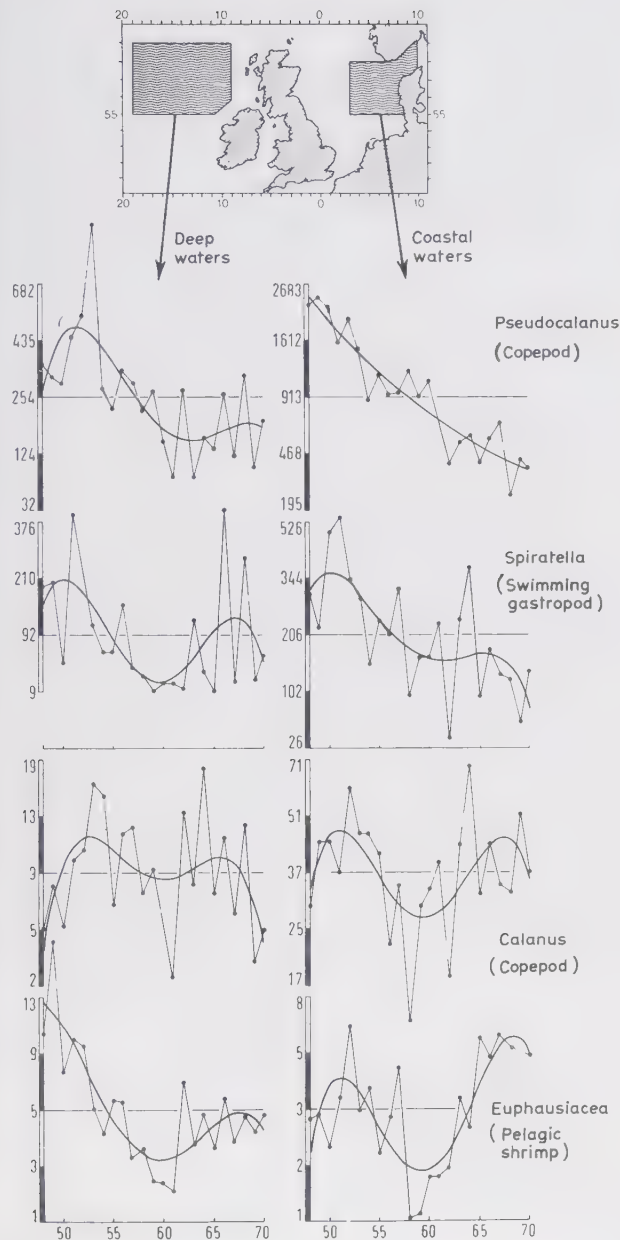
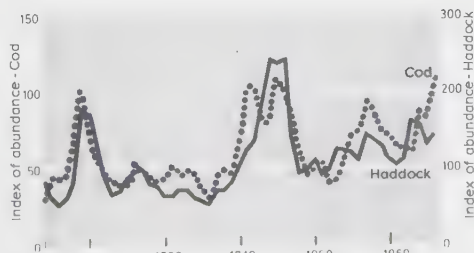


Figure 3 Annual fluctuations in the abundance of four zooplankton organisms for two areas show the dominant patterns of recent year-to-year changes. They were selected from data for about 50 species. The heavy line shows the trend derived by statistical analysis

Figure 4 The increased abundance of cod and haddock in the North Sea in recent years indicates a natural increase in productivity



decrease in winter phosphate values in the early 1930s, which were manifested biologically in important ways: the massive spring population of zooplankton dominated by *Calanus* declined, the herring fishery collapsed because of the failure of recruitment and, instead, a population of the more southerly clupeid *Sardinia* became established so that its spawning products dominated the spring zooplankton. In the mid-1960s the situation reverted to that of the 1920s: herring shoals have returned, the spring zooplankton is again abundant and dominated by *Calanus*, and other boreal fish have reappeared.

One of the best long series of quantitative data concerning marine animals is that for the commercial fish in the North Sea, which extends back to the early years of this century. Apart from the obvious effects of the two European wars, there are other important changes that cannot be easily ascribed to man's direct influence. Some of the year-to-year fluctuations, especially in haddock, clearly result from variations in year-class strength, since the numbers of young haddock surviving from the annual spawning in each spring can vary by a factor of a thousand or more. However, the distinct increasing trend that is apparent in the last few years—not only in cod and haddock, but also in plaice and other species—indicates that there has been a succession of unusually good year-classes for all the major bottom-living species. For all three species, total catches in the last few years have been higher than ever before while the abundance has been much higher than at any other period of heavy fishing (see Figure 4). Some of the increase can be credited to the international measures for conservation—prohibition of the landing of small fish, and of the use of small meshed nets—but these do not seem to be enough to explain their magnitude and there appears to have been, during the past decade, a real increase in the natural productivity of the North Sea bottom-living fish.

This review demonstrates several basic principles that have to be understood if man is to measure his influence on the ocean environment. Perhaps most important, it is evident that the ocean is a restless and changing environment and that its changes may either be sudden and dramatic, or covert and sustained for very long periods; it is also obvious that, by their nature, these changes can only be revealed and measured by deliberately mounted and well-sustained ocean monitoring operations. Less obvious there seems to be a real lack of understanding that pollution monitoring schemes, in the ocean or elsewhere, can only succeed if the natural effects of the changing physical environment are both understood and monitored continuously and indefinitely. Natural fluctuations in animal populations have already been ascribed incorrectly to the effects of pollutants, and it would be easy for a serious impact on the environment to pass unnoticed through ignorance of natural population instability or a lack of monitoring of the oceans on a global scale.

OCEANIC DISTRIBUTION OF *EVADNE* IN THE EASTERN PACIFIC (CLADOCERA)¹⁾

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While examining samples from the multiple serial plankton recorder (Longhurst et al., 1966) from the "Eastropac" expeditions, we encountered several stations more than 1000 miles offshore at which abundant cladocerans occurred in the upper mixed layer. Earlier reviews (e.g. Ramner, 1933), and recent general texts on plankton ecology (e.g. Wickstead, 1965) have suggested that cladocerans are, in general, neritic organisms, and since our samples included stations in the South Pacific central gyre, we were prompted to survey, in a rather summary fashion, the nature of the distribution of *Evadne* in the eastern part of the Pacific Ocean.

The samples examined were taken at 1011 stations, of which 927 were from the "Eastropac" expeditions, from the American coast out to about 125°W, while the remaining 84 stations were selected from earlier cruises ("Tethys", "Downwind", "Norpac", "Capricorn", etc.) to give coverage farther to the west, as far as 170°W.

The samples came, for the most part, from simple non-closing nets hauled obliquely towards the surface, mostly with a rather fine (0.3 mm) mesh. Some samples (246) were from surface tows taken with coarser nets (0.5 mm) for special purposes during the "Eastropac" cruises. No attempt was made to quantify the data on *Evadne*, since surface organisms are very irregularly sampled by such techniques as were used. Aliquots were examined of each sample for presence of specimens of *Evadne* and categorized simply as (1) absent, (2) rare (<10 specimens), and (3) abundant (>10 specimens); stations were re-examined from much larger aliquots when the initial data plots indicated negative areas in which, either a priori or because of the distribution of positive samples, we were surprised to find no *Evadne*. Thus, we are confident that the negative areas in our distributions are reasonably correct, summary though our survey was.

¹⁾ This work was partially supported by Bureau of Commercial Fisheries Contract No. 14-17-0001-989 to the Scripps Tuna Oceanography Program.

All specimens sorted from the 129 "Eastropac" stations at which *Evadne* occurred were sexed, and females were examined for presence of embryos in the brood pouch; although extremely summary, these data serve to indicate something of the reproductive biology of *Evadne* in the tropical ocean, and are summarized in table I.

Two species were encountered in the samples: specimens having divergent antennal musculature and a terminal spine and which appear to be similar to *Evadne spinifera* Müller, 1868, of the Atlantic, and specimens having parallel

TABLE I
Occurrence of males and of embryo-bearing females in the "Eastropac" samples

		northern hemisphere winter				northern hemisphere summer		
Area (see page 243)		A	B	C	D	A	B	D
Number of stations		32	13	7	14	55	3	2
Number with <i>E. tergestina</i>	♂ ♂	4	—	—	—	4	—	—
Number with <i>E. tergestina</i>	♀ ♀	29	13	7	—	54	3	2
Number of embryos/female	0	169	37	37	—	395	5	4
	1	1	—	—	—	2	—	—
	2	2	—	1	—	4	—	1
	3	12	1	1	—	8	—	—
	4	12	1	5	—	7	—	—
	5	7	3	—	—	—	1	—
	6	—	4	5	—	—	3	—
	7	—	—	—	—	—	1	—
	8	1	—	—	—	—	1	—
Number with <i>E. spinifera</i>	♂ ♂	—	—	—	—	—	—	—
Number with <i>E. spinifera</i>	♀ ♀	6	—	—	14	1	—	—
Number of embryos/female	0	26	—	—	129	1	—	—
	1	—	—	—	1	—	—	—
	2	—	—	—	2	—	—	—
	3	—	—	—	10	—	—	—
	4	—	—	—	5	—	—	—
	5	5	—	—	5	—	—	—
	6	—	—	—	—	—	—	—
	7	—	—	—	1	—	—	—
	8	—	—	—	—	—	—	—

antennal muscles and a rounded posterior profile and which are apparently referable to *Evadne tergestina* Claus, 1877. The second species was much more common than *E. spinifera*, which was restricted to certain areas. No critical examination of the specimens was made, but it is expected that they may not prove to be identical with Atlantic forms.

The apparent distribution of *Evadne* in the samples is indicated in figures 1 to 3, which show, successively, its distribution in the eastern tropical Pacific during the northern hemisphere winter; in the same region during the northern hemisphere summer; and over the whole eastern Pacific, for all seasons combined.

In the eastern tropical Pacific region the major differences in the surface circu-

lation between northern summer and winter conditions are: (1) the extent towards the coast, at around 10°N , of the Equatorial Countercurrent; (2) the extent and strength of the equatorial divergence west of the Galapagos Islands; (3) the direction and strength of the coastal currents off the west coast of Mexico. In addition, the temperature regime and the position of the thermal fronts to the north and south of the tropical regions are, of course, modified by the migration of the meteorological intertropical convergence zone.

The distribution of specimens of *Evadne* in seven samples from the multiple serial plankton sampler indicated that it occurs only in the upper part of the mixed layer in the tropical ocean. Table II shows two typical depth distributions for each species. Typically, *E. tergestina* occurred only in the surface sample, taken usually over a depth range less than the upper 10 m of the water column; *E. spinifera*, in its main area of distribution south of the equator, occurred rather deeper — down to 20 m at one station — as would be expected from the very deep mixed layer in this area. These data indicate, in summary, that *Evadne* in the eastern Pacific is an epiplankter of very shallow distribution.

DISTRIBUTION OF EVADNE TERGESTINA

Northern winter. — Samples from "Eastropac" cruises 11, 12, 13, and 14 which were concurrent during February-March 1967, showed that *E. tergestina* occurred

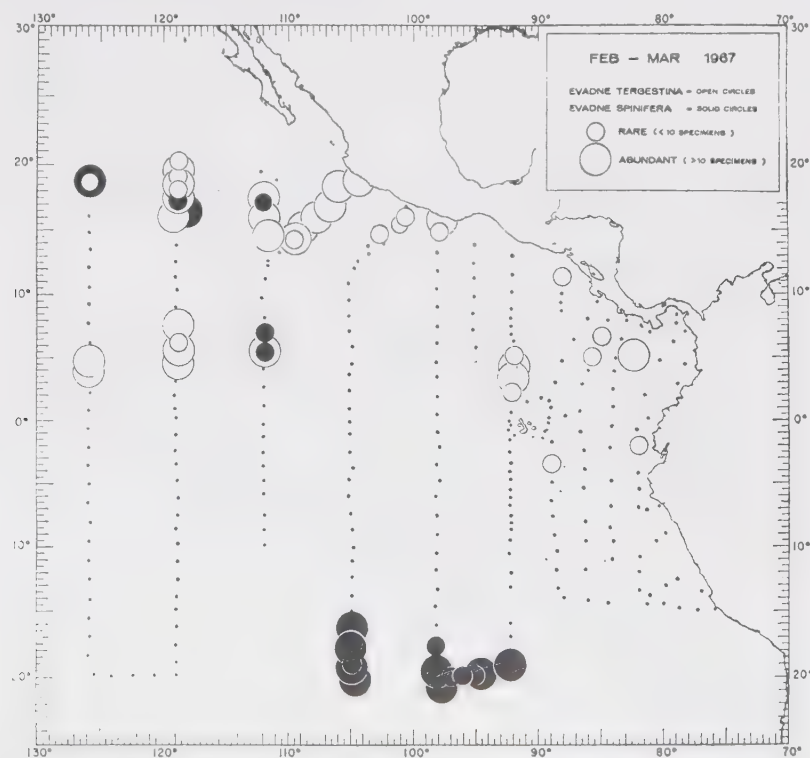


Fig. 1. Distribution of *Evadne* in the eastern tropical Pacific during the northern hemisphere winter.

TABLE II

The vertical distribution of *Evadne* in four typical multiple serial plankton sampler profiles. Numbers of individuals per 100 m³ filtered

Sample	<i>Evadne tergestina</i>				<i>Evadne spinifera</i>			
	12.018		12.244		12.154		12.164	
	Z(m)	No.	Z(m)	No.	Z(m)	No.	Z(m)	No.
1	0	201	0	167	0	548	0	110
2	8	—	10	—	4	92	12	177
3	26	—	20	12	7	27	15	88
4	48	—	35	—	10	—	25	69
5	60	—	45	5	20	—	40	36
6	78	—	60	—	30	—	55	37
7	96	—	75	—	40	—	70	56
8	110	—	80	—	50	—	80	11
9	123	—	95	—	60	—	90	—
10	138	—	110	—	70	—	110	—
11	160	—	120	—	80	—	120	—
12	175	—	135	—	85	—	135	—
13	195	—	140	—	90	—	150	—
14	210	—	155	—	105	—	105	—
15	235	—	165	—	115	—	180	—
16	252	—	180	—	125	—	195	—
17	280	—	195	—	130	—	200	—
18	290	—	205	—	135	—	220	—
19	300	—	220	—	145	—	230	—
20	318	—	230	—	150	—	240	—

in three areas of the eastern tropical Pacific (fig. 1): (A) in a belt along the western coast of Mexico and Guatemala, and extending offshore to 125°W from the latitude of central Mexico at 15 to 20°N; (B) in a zonal belt from 2°N to about 8°N far offshore, isolated from (A), and extending from about 110 to 125°W; and (C) a number of stations westwards and offshore from Ecuador and Columbia forming a less coherent distribution pattern than (A) or (B).

Within (A) most stations were positive for *E. tergestina*; the range of the species here appears to relate to the coastal current along the Central American coast, and to the southwest transport of California Current water from the region to the south of Baja California and off the mouth of the Gulf of California. The "Eastropac" stations do not indicate whether or not *E. tergestina* occurs widely north of 20°N in these longitudes, but it is likely to do so at least to 25°N off the Baja California coast; an earlier cruise (TO-64-1), at which 50 stations were scanned for *Evadne*, showed a concentration of records to the south of the Cape San Lucas Front at 23°N. and only a single occurrence farther to the north, near Punta Eugenio.

About 40% of all samples from region A showed reproductive activity, and males were present in the aliquots examined from four; females carrying three and four embryos dominated, though the number of embryos ranged from 1 to 8.

The isolated tongue of stations lying zonally about 5°N and centered at about 120°W is correlated with an incursion of warmer water from the west, being warmer than 27°C , and representing the eastward end of the Equatorial Counter-Current at a period of the year when it is least well developed in these longitudes. No males were found but embryo-bearing females occurred as frequently as in the region off the west coast of Mexico, although modal numbers of embryos appeared somewhat higher.

Between these two areas in which *E. tergestina* occurs there lies a zone in which no cladocerans were found; the reality of this zone of negative stations is based on scanning more than 70 stations, most of them with a second, confirmatory scan on a large aliquot. The zone may represent the westward flow described by Wyrтки (1965), and recognizable in the "Eastropac" physical data, which appears to originate to the south of the Costa Rica Dome and by which route some Peru Current water may find its way to the northwest.

In the third area, to the west of Costa Rica, Columbia and Ecuador, the positive records are grouped in a few locations and appear to be correlated with the distribution of warmer water; for instance, the fact that there were no records in the Gulf of Panama is probably due to the existence there of upwelling conditions at this season, seen clearly in the surface temperature distribution for February 1967. Thus, the two sets of positive stations at around 5°N are in tongues of warm water extending around the Costa Rica Dome from the coastal region; the record to the south of the Galapagos is in a tongue of warm water extending south around the Ecuadorian frontal region and the record off the Ecuadorian coast is on the warm side of this front.

Four of the samples at approximately 5°N to the west of Costa Rica and the Galapagos Islands included embryo-bearing females carrying high numbers of embryos; neither of the two samples from south of the equator showed evidence of breeding.

Northern summer. — Samples from "Eastropac" cruises 45, 46, and 47 worked during August and September 1967, showed some interesting differences from the winter pattern of distribution. At this season the northern Equatorial Counter-current is well developed and extends in a zonal band across almost the entire region, and this evidently is causative of the very considerable southerly extension of the area west of Mexico which is occupied by *E. tergestina*. The species was widespread, as during the winter period, and all except 8 of the 65 stations within this area were positive for *E. tergestina*; double-checking of samples to the south of this area served only to confirm the distributional boundary at 7 to 10°N . This boundary lies within the Equatorial Countercurrent for most of its length and coincides neither with its northerly nor southerly boundaries as shown by average climatology (Wyrтки, 1965). As during the winter survey, only a very small number of samples contained males, while the percentage with breeding females was about half what it was during the winter survey; the number of embryos

per female (predominantly 3 to 4) was similar to the number during the winter and lower than found in populations in lower latitudes.

The occurrence of positive records in the Gulf of Panama is probably related to the lack of upwelling during these months, and the stations close to the coast which introduce a gap in the continuity of the coastal distribution of the species off Costa Rica are in a region where the Costa Rica Dome induces lowered surface temperatures. Reproduction was active in this season in the Gulf of Panama and along Costa Rica, all samples containing embryo-bearing females; these were again very fecund, ranging from 5 to 8 embryos (mode 6) per female.

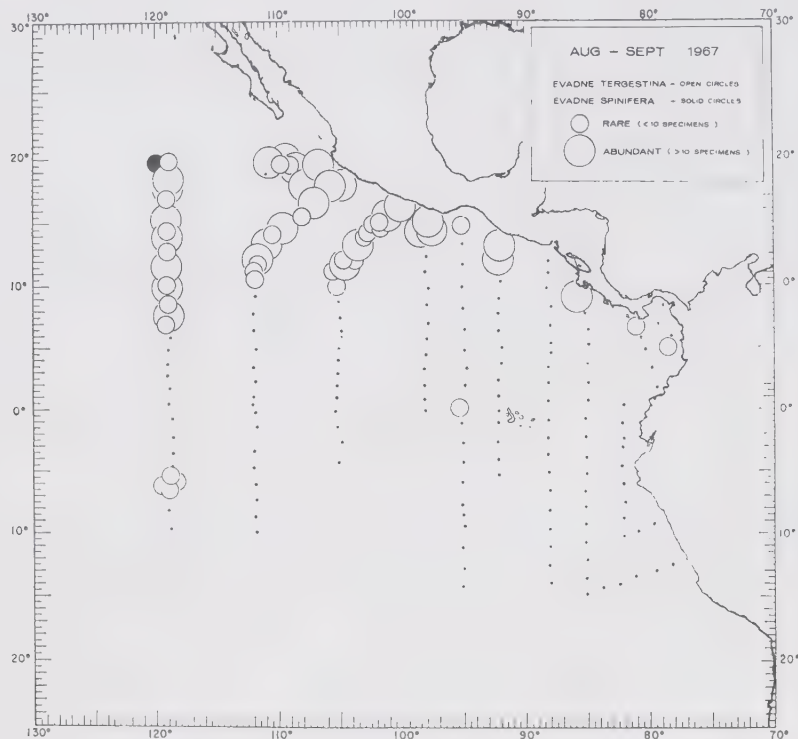


Fig. 2. Distribution of *Evadne* in the eastern tropical Pacific during the northern hemisphere summer.

The most curious occurrence is the single positive station close to the equator at 95°W; this is on the edge of the equatorial divergence, west of the Galapagos Islands in relatively cool water of 23°C and is completely isolated from other records. The positive stations at 5°S of the equator and 120°W are in a tongue or intrusion of warm water, open to the westward and which may represent the South Equatorial Countercurrent. Neither males nor embryo-bearing females occurred in these areas.

Eastern Pacific all seasons. — The data combined from 84 stations from earlier research cruises over the eastern Pacific confirmed that *E. tergestina* is not a neritic

species; however, the "Norpac" samples indicate that the major concentration off the Mexican coast does not extend significantly farther to the west than indicated by the "Eastropac" samples. The "Capricorn", "Downwind", and "Monsoon" samples combine to indicate a region at 20°S and 140 to 160°W in which a high percentage of stations indicated the presence of *E. tergestina*; this is the region of the Society, Tuamota, Cook, and Austral Islands, and it is here that islands are most frequent (albeit still sparse) in the area surveyed by these cruises. The relevance of islands to the oceanic distribution of the species may also be indicated

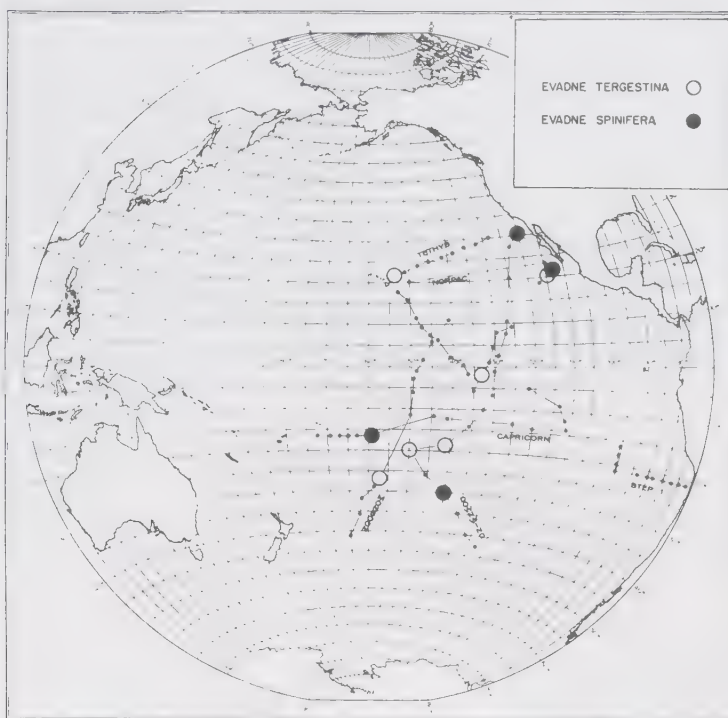


Fig. 3. Distribution of *Evadne* over the whole eastern Pacific, for all seasons combined.

by the other positive records west of the "Eastropac" region: one is just to the northeast of Hawaii, and one rather farther to the north of the Marquesas Islands.

DISTRIBUTION OF *EVADNE SPINIFERA*

The samples indicated that *E. spinifera* had a distribution quite different from that of *E. tergestina*. During "Eastropac" 11, 12, 13, and 14 in February-March 1967, the sampling lines penetrated southwards through the South Equatorial Current into the northern part of the southern Pacific central gyral water and in this area, at 90 to 110°W and 18 to 20°S, *E. spinifera* occurred in almost all the samples, sometimes abundantly. No specimens of *E. tergestina* were found in this area.

This group of occurrences lies in relatively cool ($<24^{\circ}\text{C}$) water and the location of isotherms from "Eastropac" data and the surface flow vectors of Wyrski (1965) combine to demonstrate that only those station lines which indicated *E. spinifera* distribution penetrated to the region of gyral flow; to the west, the station line at 126°W did not do so and no *Evadne* were found even in its most southerly station, nor were any found in the most southerly stations of cruise 14, off the Peruvian and Chilean coasts.

Otherwise, at two stations in the winter and at one in the summer, *E. spinifera* occurred alongside the more common species. All these occurrences were in the northwestern corner of the "Eastropac" area at around 20°N and 120°W ; the "Norpac" data confirm the occurrence of the species in this region and show it occurring also in North Pacific Central water off San Diego beyond the main stream of the California Current. It was found at only one other station, on "Downwind", in southern gyral water at 120°S 140°W to the southeast of the Austral Islands.

Males were found at only a single station (13.123 at 20°S) where 8 occurred in a sorted sample of 100 individuals. In the northern area off the Mexican coast, females with embryos were found at only a single station in winter and at no stations in the summer survey. However, in the southern area, near 20°S , 50% of the samples contained embryo-bearing females though none included males.

The number of embryos was usually moderate (mode 3) though the range extended to 7 embryos per female. The data from this survey are, of course, only for the southern hemisphere summer and no southern winter data were collected by "Eastropac" from this region, unfortunately.

DISCUSSION

It is remarkable that our records of *E. spinifera* at a group of 14 stations in the South Pacific gyre at about 20°S coincides so precisely with the location of the single previous locality for this species in the eastern Pacific (Ramner, 1933, figure 52). Samples from the Meteor Expedition (Ramner, 1931) and the earlier Plankton-Expedition (Hansen, 1899) had indicated, as summarized by Ramner (1933), that in mid and low latitudes *E. spinifera* occurred both close to the coast and in the open ocean, while *E. tergestina* occurred usually closer to the continents; Ramner's data show mid-ocean distributions of *E. spinifera* in the North Atlantic (Cape Verde Islands to Bermuda), Indian Ocean (5 to 20°S at about 80°E) and Pacific Ocean (noted above, a single station at 17°S 108°W) as well as coastal distributions in all oceans equatorwards of 50° of latitude.

Since Ramner's publication, there have been remarkably few records of ocean-wide distributions of cladocerans, most attention having been given to them in the Mediterranean Sea. Furnestin (1960) and Thiriot (1968) both speak of the neritic character of marine cladoceran distribution, though the former describes *E. spinifera* as the "least neritic" of the species she described.

In the eastern Pacific, Ramner's solitary record of *E. spinifera* has scarcely been added to since the thirties; our data indicate that, in fact, *Evadne* is as widely distributed in this ocean as Ramner showed it to be in the North Atlantic. Moreover, it appears that *E. tergestina*, far from being a neritic species, occurs widely in the great ocean spaces between New Zealand, Polynesia, and the American continent.

Although the evidence is not very clear (so vast is the area), our data suggest that *E. spinifera* in the eastern Pacific is primarily a species of central gyral waters, while *E. tergestina* avoids these water masses and occurs widely but irregularly in warm waters at low latitudes. Such an observation is supported by the data of Thiriot (1968) on three species of *Evadne* in the Mediterranean: he found (1) that *E. tergestina* seems to avoid high concentrations of *E. spinifera* and (2) that *E. spinifera* appears first in the spring and develops large populations in water temperatures of 16 to 21°C, while *E. tergestina* appears only later and has an optimal temperature in excess of 22°C.

Because of his lack of records of *E. spinifera* from the Meteor Expedition in the central South Atlantic, and because of a supposed correlation between its North Atlantic distribution and that of floating *Sargassum* fronds, Rammner (1933) doubted that this was a truly oceanic species. He suggested that the nuchal organ was used for attachment to floating objects in the same manner as in *Sida cristallina* and other fresh-water cladocerans.

We suggest, however, that our data show that at least two species of *Evadne* are members of the oceanic epiplankton, having an ocean-wide distribution in the Indo-Pacific. Moreover, in some oceanic areas at some seasons, both *E. tergestina* and *E. spinifera* occur abundantly and in a high proportion of samples.

RÉSUMÉ

Il est montré, après examen de plus d'un millier d'échantillons de zooplancton de l'Océan Pacifique de l'est, que *Evadne tergestina* et *E. spinifera* sont répandues largement dans l'épiplankton océanique, confirmant ainsi les observations de Rammner pour l'Atlantique Nord. *E. spinifera* vit typiquement dans les régions courants gyroïdes centraux, et *E. tergestina* est répandue plus largement dans les eaux chaudes de la zone tropicale; tous les deux évitent les eaux plus froides des régions d'upwellings même sous l'équateur.

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ON THE CLARIFICATION OF LARVAL TUNA IDENTIFICATION PARTICULARLY IN THE GENUS *Thunnus*

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ABSTRACT

A Larval Tuna Identification Workshop was held at the Bureau of Commercial Fisheries Biological Laboratory (now the National Marine Fisheries Service, Southwest Fisheries Center), Honolulu, Hawaii, on March 2-6, 1970, to resolve conflicting views on the identification of larvae of *Thunnus alalunga* and *T. albacares* and to clarify the status of larval identification of other *Thunnus* species.

The identification of *T. alalunga* (Yabe and Ueyanagi, 1962), *T. albacares* (Matsumoto, 1958), *T. obesus* (Matsumoto, 1962), and *T. thynnus* (Yabe, Ueyanagi, and Watanabe, 1966) was agreed upon as correct, except that the description of *T. albacares* should include the appearance of black pigmentation at the tip of the lower jaw when the larva attains a length of about 4.5 mm SL and that the lower size limit of reliable identification of *T. alalunga* be set at about 4.5 mm SL until further studies indicate more precisely whether the black pigmentation at the tip of the lower jaw in *T. albacares* appears earlier. There was no difference in appearance of *T. thynnus* larvae from the Atlantic and Indo-Pacific Oceans. The identification of *T. tonggol* and *T. maccoyii* larvae was not conclusive. The larvae of *T. atlanticus* required further study.

The workshop further concurred that juveniles (13-200 mm SL) of several species of *Thunnus* may be separated by internal and external characters: *T. atlanticus* by vertebral count, *T. alalunga* by shape of first elongate haemal spine and arrangement of pterygiophores of the second dorsal fin relative to two adjacent neural spines, and *T. thynnus* by configuration of lateral line and arrangement of pterygiophores of the second dorsal fin; and that juveniles of *T. obesus* and *T. albacares* may be separated from the previous three species by arrangement of pterygiophores of the second dorsal fin, but not from each other.

The proper identification of larval tunas has been a perplexing and difficult problem for many years. Although progress in the past two decades has resulted in agreement on the identification of larvae of a number of species (*Katsuwonus pelamis*, *Euthynnus alletteratus*, *E. affinis*, *E. lineatus*, *Thunnus thynnus*, *T. obesus*, and *Auxis* spp.), there is still some disagreement

and confusion on the identity and description of *T. alalunga* and *T. albacares*. At the present time there are two different descriptions given for *T. alalunga* (Matsumoto, 1962; Yabe and Ueyanagi, 1962). The identity of other tunas, such as *T. tonggol*, *T. maccoyii*, and *T. atlanticus*, has yet to be confirmed or resolved.

One of the chief problems in larval tuna identification is the difficulty in obtaining good series of larvae for study. Tuna larvae are seldom taken in sufficient numbers by the usual collecting methods, and individuals over 10 mm standard length (SL) are taken rather infrequently. Additionally, although the young of a number of tuna species are found together in many parts of the ocean, some species are localized in certain areas. Consequently, it is extremely difficult for workers in different parts of the world to have

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at hand a complete series of larvae of more than two to four species.

In an attempt to resolve the conflicting views on *T. alalunga* and to review the identification of larvae of other species of tunas, a Larval Tuna Identification Workshop was held at the Bureau of Commercial Fisheries (BCF) Biological Laboratory (now the National Marine Fisheries Service, Southwest Fisheries Center), Honolulu, Hawaii, on March 2-6, 1970. The workshop also afforded an opportunity to workers specializing on larval tuna identification to assemble specimens of the various species of tunas and to examine these together. The procedure followed at the workshop was (1) to summarize the status of larval tuna identification to date by species and (2) to evaluate the identifying characters by examining larval specimens. As time permitted, the status of juvenile tuna identification was also examined.

The participants included:

Mr. Walter M. Matsumoto, Convenor

Dr. Elbert H. Ahlstrom, Advisor

Dr. Santhappan Jones

Mr. Witold L. Klawe

Dr. William J. Richards

Dr. Shoji Ueyanagi

Dr. Jean-Yves Le Gall of the Centre Océanologique de Bretagne, Brest, France, attended the workshop as an observer.

The sessions were conducted informally with a summary of the present status of larval tuna identification, including recent developments, followed by evaluation of the various characters that could be relied upon for positive identification. Most of the sessions were devoted to direct examination of larval specimens of the various species and discussions of unpublished data offered by participants.

This report summarizes the proceedings and results of the workshop.

RECENT DEVELOPMENTS IN THE IDENTITY OF *Thunnus alalunga*

Two differing versions of the identity and description of *T. alalunga* had arisen from reliance on black pigmentation in different parts of the body. Matsumoto (1962) relied upon black pig-

mentation on the dorsal and ventral edges of the trunk forward of the caudal fin base, whereas Yabe and Ueyanagi (1962) relied upon black pigmentation on the tips of the upper and lower jaws and the absence of pigmentation on the trunk.

The lack of sufficient larvae fitting Matsumoto's description from areas presumed to be spawning grounds on the basis of gonad studies casts some doubt on his identification. On the other hand, good correspondence in the occurrence of larvae fitting Yabe and Ueyanagi's description with catches of adult *T. alalunga* in various areas in the Pacific seemed to support the latter identification. A study of red pigment patterns in larvae prior to preservation (Ueyanagi, 1966) reinforced Yabe and Ueyanagi's identification and description. Additional observations on red pigmentation by Matsumoto (see later discussion) confirmed Ueyanagi's results and also provided more data to enhance the reliability of red pigmentation as a supplementary character for identifying *T. alalunga*.

IDENTIFICATION OF TUNA LARVAE

With the problem of differences in the identity and description of *T. alalunga* larvae fairly well settled at the outset, there remained the tasks of evaluating the various identifying characters, not only for this species but for other tunas as well, and of describing the species at various size categories.

DEFINITION OF LARVA

In tunas, as in many other fish, it is difficult to clearly separate the larval from the juvenile stages because there is no marked metamorphosis and the usual adult characters used for species identification develop gradually and separately. It is generally accepted among workers in larval tunas that the larval stage ends when the larva has developed the full complement of spines and rays in all the fins, all the vertebrae have ossified, and the anal opening has moved back near the origin of the anal fin. For nearly all tuna species, these developments occur when the larva has attained 10 to 13 mm SL. We use this as our definition, also.

EVALUATION OF CHARACTERS

In identifying fish larvae collected in plankton nets, the easiest and perhaps the only recourse is to identify the largest stage and work down to the smallest. Unfortunately, very few tuna larvae above 9 mm SL are taken in plankton net tows so that this process cannot be followed at all times and identification, therefore, must depend upon those nonadult characters that are the most distinctive and consistent throughout the size range.

Characters that have been used in the past were reviewed and evaluated. A résumé of the usefulness of the various characters follows.

Meristic

The number of myomeres is useful in separating *Katsuwonus pelamis* (42-43) and *Euthynnus lineatus* (38-39) from other tunas, including other species of *Euthynnus*, all of which have similar numbers of myomeres (40-41). The number of fin rays and spines are not useful for separation of *Thunnus* because all species are similar in this respect.

Morphological

Shape of first dorsal fin, when completely formed, is useful to distinguish late larval stages of *K. pelamis*, *Euthynnus*, and *Auxis* from those of *Thunnus*. Preopercular spines are unreliable because they undergo rapid growth changes and position of eye relative to longitudinal axis of body needs to be determined more accurately. Distribution (number and position) of pterygiophores in the second dorsal fin in relation to neural spines is useful in separating several *Thunnus* species, but only after these bones have ossified in larvae longer than 10 mm SL. Other characters of the axial skeleton useful in identification, such as the position of the first haemal arch and the position of the zygapophyses on the vertebrae, also form late.

Measurements

Morphometrics have not been used extensively to date, although there may be some with good possibilities, such as the relations of body depth to standard length, snout length to head length,

and snout length to orbit diameter. Some of the reasons for not using measurement data are that the larvae not only shrink in preservatives, but the degree of shrinkage varies in different preservatives and with duration of preservation; the distortion of the body at the time of fixing cannot be controlled; and, more important, there are too few larvae in undistorted condition for reliable measurements. Added to these are other sources of variability such as rapid changes in body parts due to growth, changes which often occur in spurts, and distension of the abdomen, as well as stretching of the body at each feeding.

Pigmentation

For the most part black pigment patterns have been the most widely used and accepted character in identifying tuna larvae. There are variations and changes in black pigment patterns on tuna larvae due to growth, but in certain areas of the body these patterns have been found to be consistent enough for identification purposes. This is particularly true of pigment patterns on the first dorsal fin, posterior half of the trunk, forebrain, and tips of both jaws. The larval size at which black pigment cells appear in certain areas of the body, especially at the upper and lower jaw tips, may be useful in separating *T. albacares* from *T. alalunga*. Red pigment patterns, although not species specific, have been useful in confirming the identification of *T. alalunga* when used in conjunction with black pigment patterns.

Of all the characters reviewed and examined, pigment patterns, both black and red, were considered to be the most reliable for identification of the larval stages, despite their known variability, when supplemented by the use of certain morphological characters such as the distribution of pterygiophores in the second dorsal fin and characteristics of the vertebral column, whenever these are developed.

VERIFICATION OF RED PIGMENTATION

Ueyanagi (1966) reported on the usefulness of red pigmentation in identifying tuna larvae. Up to then identification of tuna larvae by pigmentation had been based on black pigment only.

Ueyanagi examined 350 larvae and concluded that *T. albacares* and *T. alalunga*, which are difficult to identify by the usual diagnostic characters, could be distinguished by differences in red pigment patterns: larvae of *T. alalunga* consistently had more red pigment spots on the dorsal and ventral edges of the body and along the mid-lateral line forward of the caudal peduncle than larvae of *T. albacares*; red pigment patterns in larvae of *T. thynnus* and *T. obesus* were intermediate between those of *T. alalunga* and *T. albacares*; the red pigment pattern in *Allothunnus fallai* was similar to that in *Thunnus*; and the pattern in *K. pelamis* resembled that in *Auxis* spp. and *E. affinis* but differed from that in *Thunnus*.

To confirm these results and to provide additional information on red pigmentation in tuna larvae, the results of observations made on 432 larvae taken in Hawaiian waters during August and September 1967 were presented. Tables 1 and 2 give the number of red pigment cells along the dorsal, ventral, and lateral lines on the posterior half of the trunk and a summary of the number of larvae examined, the number of larvae observed with red pigmentation, and the mean numbers of red pigment cells at the three sites. In Table 2, the number of red pigment cells observed most frequently are given in bold face type and those observed occasionally or seldom are enclosed in parentheses.

The pigment patterns agreed generally with those reported by Ueyanagi for the species listed in the tables. Differences in the patterns were noticeable mainly in the dorsal edge of the trunk and, to a lesser extent, in the mid-lateral line. There was no significant difference in the number of pigment cells between the left and right sides of the body.

The appearance and extent of red pigment cells varied in larvae taken in night and day tows. In larvae taken at night the pigment cells were numerous, distinct, and brightly colored, whereas in larvae taken during the day the pigment cells were faintly colored, often not visible, and in many instances the pigment spots were united, forming single continuous lines. Of the species taken in both day and night tows (*T. albacares*, *T. obesus*, and *K. pelamis*), red pigmen-

tation was not visible in 41.5% of the larvae taken during the day, compared with only 3.6% of the larvae taken at night. Thus, observations of red pigment cells must be made largely on larvae taken at night to reduce the effects of diel variations.

Despite the variations, red pigmentation is a useful supplementary character to either separate certain species or verify the identification made on the basis of other characters. That the red pigment pattern is not species specific is clearly seen in the similarity among *K. pelamis*, *Auxis* spp., and *E. affinis* and between *T. obesus* and *T. albacares*; however, it is useful in separating *T. alalunga* from the other kinds of *Thunnus*.

EXAMINATION AND DISCUSSION OF SPECIES

Thunnus alalunga and *T. albacares*

Larvae of these two species were examined together because they are the only species lacking black pigment cells on the trunk, exclusive of the caudal fin and abdomen (Yabe and Ueyanagi, 1962). Characters, including some that have not been used in the past, for separating the two species are summarized in Table 3. The larval stage was divided into two size categories, small larvae less than 10 mm SL and larger larvae 10 to 13 mm SL, because the characters used in differentiating small larvae became ineffective or obscured with growth. As mentioned earlier, pigmentation, particularly the presence of black pigment cells at the tips of the upper and lower jaws and the amount of red pigment cells on the trunk, was the most reliable character in separating larvae of the two species.

In small larvae, black pigment cells on the lower jaw tip were first observed in larvae of *T. albacares* about 4.5 to 6.0 mm SL, and often as small as 3.8 mm SL; those on the upper jaw tip were first observed in larvae about 7.0 mm SL (Figures 1 and 2, reproduced from Matsumoto, 1958⁷). In *T. alalunga* these pigment cells were

⁷ The difference in developmental stages per given size in the figures by Matsumoto (1958) and Ueyanagi (1969) is due to method of preservation: Matsumoto's figures are of larvae preserved in 10% Formalin; Ueyanagi's figures are of larvae preserved in 70% alcohol.

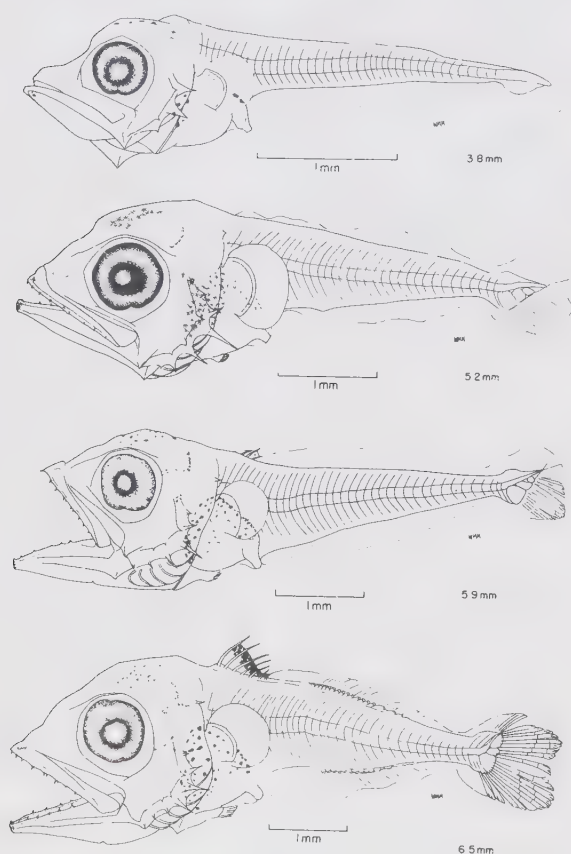
TABLE 1.—Frequency of red pigment cells in larval tunas from Hawaiian waters, August-September 1967.

Part of body	No. of pigment cells	<i>Thunnus albacares</i>			<i>Thunnus obesus</i>			<i>Thunnus alalunga</i>			<i>Katsuwonus pelamis</i>			<i>Axiis</i> spp.			<i>Euthynnus affinis</i>		
		Left side	Right side	Percent occurrence ¹	Left side	Right side	Percent occurrence ¹	Left side	Right side	Percent occurrence ¹	Left side	Right side	Percent occurrence ¹	Left side	Right side	Percent occurrence ¹	Left side	Right side	Percent occurrence ¹
Dorsal edge trunk	0	56	52	51.9	26	26	57.7	--	--	--	86	87	99.4	49	20	94.5	8	7	100.0
	1	42	32	35.6	16	18	37.7	--	--	--	--	--	--	2	2	5.5	--	--	--
	2	10	9	9.1	4	--	4.4	3	3	46.1	1	1	0.6	--	--	--	--	--	--
	3	4	2	2.9	--	--	--	3	3	46.1	--	--	--	--	--	--	--	--	--
	4	--	1	0.5	--	--	--	1	--	7.7	--	--	--	--	--	--	--	--	--
Total		112	96	--	46	44	--	7	6	--	87	88	--	51	22	--	8	7	--
Mid-lateral line trunk	0	4	9	6.3	11	8	21.6	--	--	--	85	86	97.7	35	16	70.0	6	7	86.7
	1	12	11	11.2	6	8	15.9	--	--	--	1	1	--	13	5	24.6	--	--	--
	2	45	34	38.3	11	13	27.3	--	1	7.7	1	1	1.1	2	1	4.1	1	--	6.7
	3	31	24	26.7	10	8	20.4	3	2	38.4	--	1	0.6	1	--	1.4	1	--	6.7
	4	14	14	13.6	7	5	13.6	3	3	46.1	--	--	--	--	--	--	--	--	--
Total		6	1	--	--	--	--	1	1	7.7	--	--	--	--	--	--	--	--	--
Ventral edge trunk	0	111	95	--	45	43	--	7	6	--	87	88	--	51	22	--	8	7	--
	1	--	--	0.5	--	1	1.2	--	--	--	1	--	0.6	--	--	--	--	--	--
	2	1	--	--	2	--	2.4	--	--	--	2	2	2.3	--	--	--	--	--	--
	3	2	7	4.6	3	4	8.6	--	--	--	3	5	4.6	4	2	8.2	--	--	--
	4	6	9	7.7	7	5	14.8	--	--	--	5	5	5.7	4	--	5.5	--	--	--
Total	5	13	16	14.9	12	10	27.1	1	--	--	6	4	5.7	3	1	5.5	1	3	26.7
	6	19	14	17.0	8	10	22.1	2	--	--	9	12	12.0	2	5	9.6	1	3	20.0
	7	22	14	18.5	5	4	11.1	1	3	30.8	8	8	9.0	3	1	5.5	3	--	6.7
	8	14	12	13.4	4	3	8.6	2	--	15.4	7	12	10.8	5	2	9.6	1	2	20.0
	9	6	7	6.7	--	1	1.2	--	1	13.4	12	10	12.6	3	1	5.5	2	--	13.3
Total	10	7	5	6.2	--	--	--	--	1	7.7	6	10	9.1	8	4	16.4	1	--	6.7
	11	3	2	2.6	--	--	--	--	1	7.7	6	5	6.3	1	1	2.7	--	--	--
	12	3	1	2.1	--	1	1.2	1	1	15.4	1	4	3.9	6	1	9.6	--	--	--
	13	1	--	0.5	--	--	--	--	--	--	--	--	0.6	1	1	1.4	--	--	--
	14	2	1	1.5	--	--	--	--	--	--	2	1	1.7	2	--	2.7	--	--	--
Total	15	--	2	1.0	--	--	--	--	--	--	1	1	1.1	--	--	--	--	--	--
	16	1	--	0.5	--	--	--	--	--	--	1	1	0.6	--	--	--	--	--	--
	17	--	--	--	--	--	--	--	--	--	--	--	0.6	--	--	--	--	--	--
	18	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	19	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total		103	91	--	42	39	--	7	6	--	87	88	--	51	22	--	8	7	--

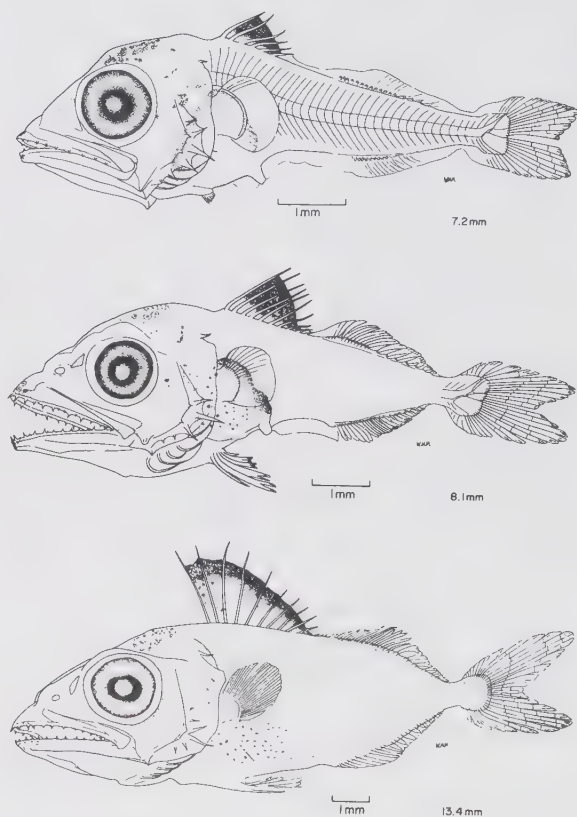
¹ Percent occurrence refers to left and right sides combined.

TABLE 2.—Summary of red pigment cells in larval tunas from Hawaiian waters, August-September 1967.

Species	Number larvae examined	Larvae with red pigment	Red pigment cells on posterior half of trunk					
			Dorsal edge		Mid-lateral line		Ventral edge	
			Number ¹	Mean	Number ¹	Mean	Number ¹	Mean
<i>Thunnus albacares</i>	130	112	0, 1, 2, (3)	0.6	(0), 1, 2, 3, 4, (5)	2.4	3-12	7.0
<i>Thunnus obesus</i>	63	47	0, 1, (2)	0.5	0, 1, 2, 3, 4	1.9	1-8	5.3
<i>Thunnus alalunga</i>	6	6	2, 3, (4)	2.6	(2), 3, 4, (5)	3.5	5-12	8.0
<i>Katsuwonus pelamis</i>	138	88	0	0.0	0	0.0	1-12	7.2
<i>Auxis</i> spp.	72	51	0, (1)	0.0	0, 1, (2)	0.4	2-14	7.6
<i>Euthynnus affinis</i>	23	8	0	0.0	0, (2), (3)	0.3	4-10	6.7
Total	432	312						

¹ Less than 2% occurrence omitted.FIGURE 1.—Larval stages of *Thunnus albacares*, I. (From Matsumoto, 1958. Lengths have been converted from total to standard.)

first observed on the upper jaw tip in larvae about 5.0 mm SL and on the lower jaw tip at about 9.0 to 10.0 mm SL (Figures 3 and 4, reproduced from Ueyanagi, 1969). Consequently,

FIGURE 2.—Larval stages of *Thunnus albacares*, II. (From Matsumoto, 1958. Lengths have been converted from total to standard.)

all larvae between 4.5 and 7.0 mm SL having black pigment cells only on the lower jaw tip, and larvae between 7.0 and 9.0 mm SL having black pigment cells on the tips of both jaws were considered as *T. albacares*. All larvae between 5.0 and 9.0 mm SL having black pigment cells

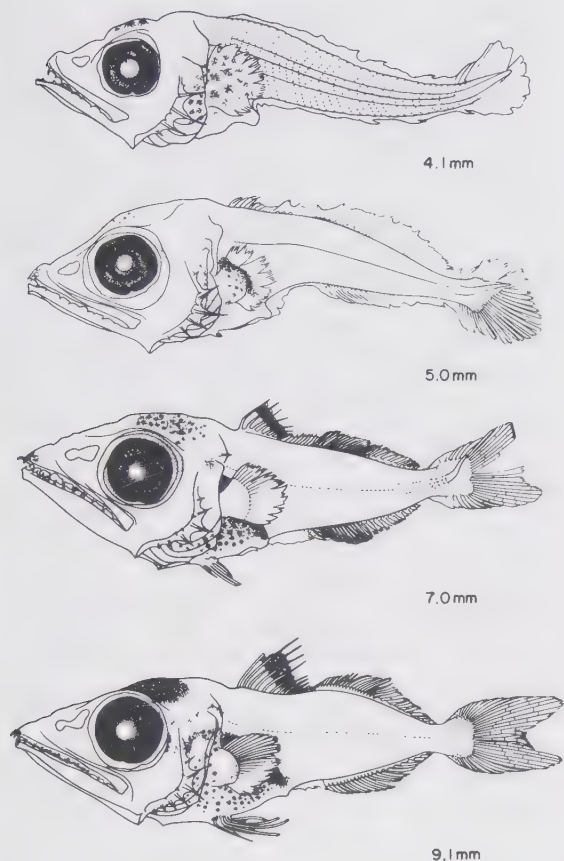


FIGURE 3.—Larval stages of *Thunnus alalunga*, I. (From Ueyanagi, 1969. Lengths have been converted from total to standard.)

only on the upper jaw tip were considered as *T. alalunga*. Larvae of the two species from 9.0 to 10.8 mm SL were separated by the position of black pigment cells on the lower jaw tip: in *T. albacares* the pigment cells were located on the inner, and sometimes outer, margins in larvae up to 10.8 mm SL, but in *T. alalunga* they were found only on the outer margin. It is suspected that the black pigment cells on the inner margin of the jaw in *T. albacares* migrate to the outer margin with further growth of the larvae.

Red pigmentation was accepted as a good supplementary character for separating *T. albacares* from *T. alalunga* (Tables 1 and 2). The distinc-

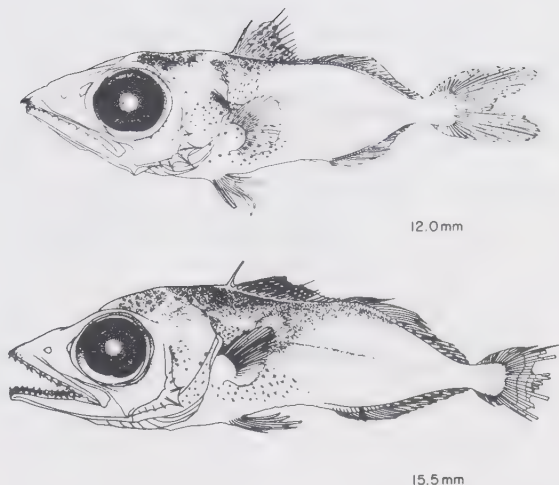


FIGURE 4.—Larval stages of *Thunnus alalunga*, II. (From Ueyanagi, 1969. Lengths have been converted from total to standard.)

tive patterns were located along the dorsal margin of the trunk from about the midpoint of the second dorsal fin base to the caudal peduncle. In *T. albacares* there was usually none or one red pigment cell at the caudal peduncle. Two pigment cells occurred seldom and three or four pigment cells occurred only rarely. Generally, these pigment cells were clustered at the caudal peduncle region. In *T. alalunga* there were usually two or three pigment cells, sometimes as many as four. Unlike those in *T. albacares*, these pigment cells were well spaced, extending forward to the middle of the second dorsal fin base. Only minor differences were noted in the red pigment cells along the mid-lateral line.

In larger larvae (10–13 mm SL) differences in the two species were noted in the distribution of pterygiophores of the second dorsal fin on cleared and stained specimens (Table 3). In *T. albacares* the two successive single pterygiophores between two adjoining neural spines occurred at the posterior end, whereas in *T. alalunga* they were at the anterior end. Additionally, the first haemal arch was on the 11th vertebra in *T. albacares* and on the 10th vertebra in *T. alalunga*.

TABLE 3.—Characters to separate larvae of *Thunnus albacares* and *Thunnus alalunga*.

Characters	<i>T. albacares</i>	<i>T. alalunga</i>
Small larvae (4-10 mm SL):		
Black pigmentation:		
Upper jaw	Appears at about 5.8 mm SL, mostly after 6.0 mm SL	Appears at about 5.0 mm SL
Lower jaw	Appears at 4.5-6.0 mm SL At tip on inner edge; migrate to outer edge with further growth	Appears at 9-10 mm SL At tip on outer edge
Red pigmentation:		
Dorsal edge body, postanus	0, 1, 2, (3) [mean = 0.6]; near caudal peduncle	2, 3, (4) [mean = 2.6] from peduncle to mid-second dorsal fin base
Lateral line, postanus	(0), 1, 2, 3, 4, (5) [mean = 2.4]	(2), 3, 4, (5) [mean = 3.5]
Ventral edge body, postanus	3-12 [mean = 7.0]	5-12 [mean = 8.0]
Large larvae (>10 mm SL):		
Array of 1 st Da pterygiophores between two adjacent neural spines	1, 2, 2, 2, 3, 2, 1, 1	1, 1, 2, 2, 2, 3, 2, 1
Position of first haemal arch (vertebra number)	11th	10th

¹ D₂ refers to second dorsal fin.

Other *Thunnus* species

These species, which include *T. thynnus* (*T. thynnus thynnus* of Atlantic and *T. thynnus orientalis* of Pacific), *T. tonggol*, *T. maccoyii*, and *T. obesus*, have been identified mainly by black pigmentation on the trunk other than that over the abdominal wall.

In small *T. thynnus* of both Atlantic and Pacific Oceans (larvae between 3 and 10 mm SL), one or two large black pigment cells are present on the dorsal edge of the trunk between the second dorsal and caudal fins (Table 4, Figures 5 and 6), the anterior one usually being the larger. There may also be one to four black pigment cells on the ventral edge of the trunk between the anus and the caudal fin. Black pigmentation in *T. thynnus* from both oceans agrees quite well, except that in 5 out of 10 Atlantic specimens one or two tiny black pigment cells were noted along the mid-lateral line of the body near the pectoral fin, and in two instances a single tiny black pigment cell was found on the mid-lateral line beneath the posterior end of the second dor-

sal fin. These pigment cells were not considered reliable for identification purposes.

Observation of red pigmentation on larvae of Atlantic and Pacific *T. thynnus* is incomplete. Only one Atlantic *T. thynnus* larvae was examined for this character, but unfortunately the specimen was taken in a day tow so that the pigmentation appeared as a continuous streak on both the dorsal and ventral edges of the trunk as well as on the ventral surface of the lower jaw. In Pacific *T. thynnus* there were one to five red pigment cells, usually three, on the dorsal edge of the trunk. The number of red pigment cells on the mid-lateral line and ventral edge of the trunk has not been recorded, but according to the illustration by Ueyanagi (1966), the pigment pattern may be similar to that of *T. obesus*. On the basis of black and red pigmentation, the Atlantic and Pacific *T. thynnus* were not separable.

The identification of *T. tonggol*, based on size series of 4.2 to 7.3 mm, has yet to be confirmed. Following the description of the species by Matsumoto (1962), larvae similar to these having the anteriormost black pigment cell on the dorsal edge of the body ahead of the second dorsal fin origin have been found in 1963 in the mid-South Atlantic Ocean near Ascension Island. Confirmation of the species description requires the finding of adults within this area and the finding of additional larvae to extend the identified size range.

The identification of *T. maccoyii*, which was first described as having black pigment pattern similar to that of *T. thynnus* (Yabe, Ueyanagi, and Watanabe, 1966) and later as having the black pigment cells on the dorsal edge of the trunk reduced to pinpoints (Ueyanagi, 1969), also needs verification (see discussion on *T. thynnus*). The correspondence of published descriptions based on eight specimens and observations of larvae identified as this species were not conclusive.

T. obesus was easily separated from *T. thynnus* by the absence of black pigmentation on the bases of the anterior dorsal finlets. Sometimes a single small black pigment cell was present along the ventral edge of the trunk near the caudal peduncle, but more often one to three pig-

TABLE 4.—Characters used to separate larvae of *Thunnus* species having black pigmentation on trunk.

Characters	<i>Thunnus thynnus</i> (Atlantic)	<i>Thunnus thynnus</i> (Pacific)	<i>Thunnus tonggol</i>	<i>Thunnus maccoyii</i>	<i>Thunnus obesus</i>
Small larvae (3-10 mm SL):					
Number of black pigment cells:					
Upper jaw tip	No observation	Appears above 6 mm SL	No observation	Appears above 5 mm SL	Few spots above 5 mm SL
Lower jaw tip	2 on inner edge	2 on inner edge above 4 mm SL	No observation	Appears above 4 mm SL	0-2 on inner edge below 4 mm SL
Dorsal edge trunk	1 or 2	1 or 2	1, 2, or more	1 or 2, very small	None
Lateral line	0-2 near mid-trunk	None	None	0 or 1 near mid-trunk	None
Ventral edge trunk	1-4	2 or more	2 or more	1-3	1 or more
Number of red pigment cells:					
Dorsal edge trunk	Streak on caudal peduncle ¹	1-5, mostly 3	No observation	No observation	0, 1, (2)
Lateral line	Indistinct ¹	Number not available	No observation	No observation	0, 1, 2, 3, 4
Ventral edge trunk	Streak anus to caudal peduncle ¹	Number not available	No observation	No observation	1-8 [mean = 5.3]
Lower jaw ventral view	Streak along margin anterior half of jaw and midline ¹	2 well spaced on anterior half	No observation	No observation	1 on each side near tip
Large larvae (>10 mm SL):					
Array of 2D ₂ pterygiophores between two adjacent neural spines	1, 2, 2, 3, 2, 2, 1, 1	No observation	No observation	No observation	1, 2, 2, 2, 3, 2, 1, 1

¹ Only one larva taken in a day tow was examined.² D₂ refers to second dorsal fin.

ment cells were present along the base of the posterior half of the anal fin. Red pigmentation did not differ from that in *T. albacares*.

In larger larvae (10-13 mm SL) the array of pterygiophores of the second dorsal fin between two adjacent neural spines was sufficient to separate *T. thynnus* from *T. obesus* and both species from *T. alalunga* (Tables 2 and 3). In *T. thynnus* the greatest number of pterygiophores (3) between two adjacent neural spines appeared in the fourth position in the array, whereas in *T. obesus* and *T. alalunga* it appeared in the fifth and sixth positions, respectively. *T. obesus* was not distinguishable from *T. albacares* by this character.

The identification of *T. atlanticus* was not resolved. No larvae from the distributional range of this species (tropical western Atlantic) have been found which are distinguishable from any of the species considered above. One of us (Richards) suspects that *T. atlanticus* larvae are very similar to larvae of *T. obesus*. This suspicion is based on the great abundance of larvae resembling those of *T. obesus* in this area, particularly at times and places where *T. obesus*

adults are rarely found or absent. Further studies are needed.

SUMMARY OF LARVAL IDENTIFICATION

On the basis of the examination and discussion above, the workshop agreed that:

1. The description of *T. albacares* by Matsumoto (1958) was correct (see Figures 1 and 2), but that the "appearance of black pigmentation at the tip of the lower jaw at about 4.5 mm SL" should be included.

2. The description of *T. alalunga* by Yabe and Ueyanagi (1962) and illustrations by Ueyanagi (1969) were correct (see Figures 3 and 4), but that the lower size limit should be set at about 4.5 mm SL until further studies indicate more precisely the earlier appearance of black pigmentation at the tip of the lower jaw in *T. albacares*.

3. It is not possible to separate larvae of *T. albacares* from *T. alalunga* below 4.5 mm SL, prior to the appearance of black pigment cells at the tip of the lower jaw in *T. albacares*.

4. The description of *T. thynnus* by Yabe, Ueyanagi, and Watanabe (1966) was correct

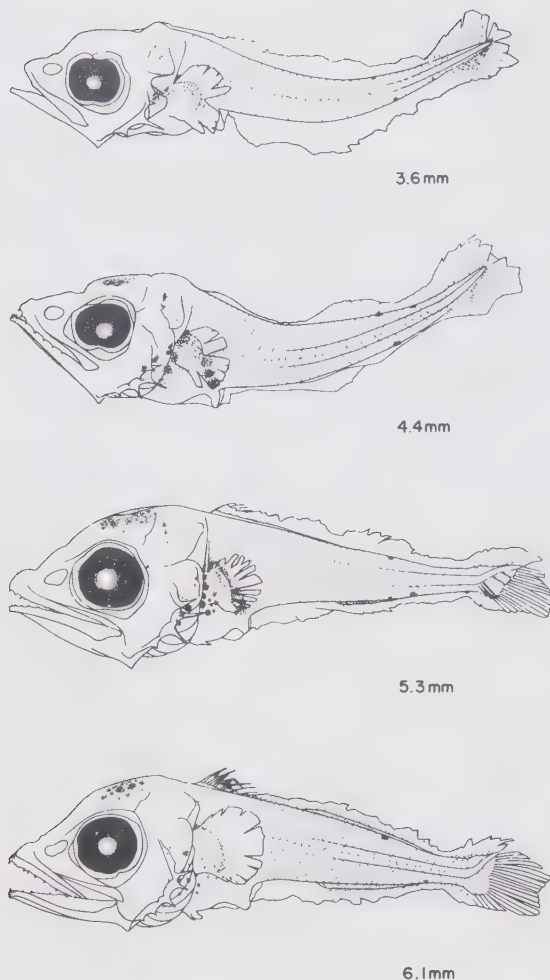


FIGURE 5.—Larval stages of *Thunnus thynnus*, I. (From Yabe, Ueyanagi, and Watanabe, 1966. Lengths have been converted from total to standard.)

(see Figures 5 and 6), and that there was no difference in *T. thynnus* from the Atlantic and Pacific Oceans.

5. The identification of *T. tonggol* was not substantiated by an adequate size series.

6. The description of *T. maccoyii*, based on tiny melanophores on the dorsal edge of the trunk, was not conclusive.

7. The description of *T. obesus* by Matsumoto (1962) was correct, though it needed to be augmented by illustrations of a complete size series.

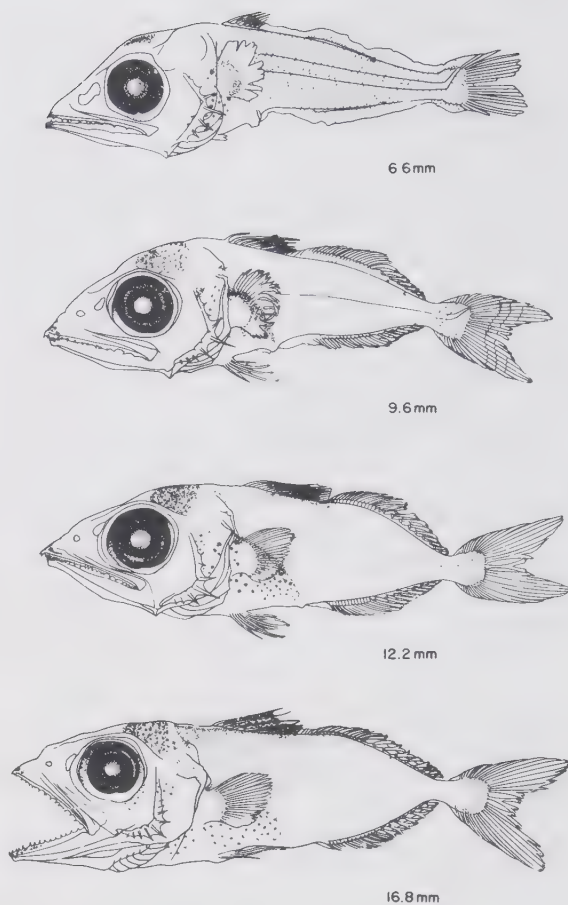


FIGURE 6.—Larval stages of *Thunnus thynnus*, II. (From Yabe, Ueyanagi, and Watanabe, 1966. Lengths have been converted from total to standard.)

8. The identity of *T. atlanticus* larvae is unresolved.

IDENTIFICATION OF JUVENILES

In spite of the intention of the workshop to assemble as many specimens of juvenile tunas as possible, only a few juveniles of *T. albacares* and *T. obesus*, not nearly enough to warrant their detailed examination, were available for study. The discussion on juvenile tuna identification, therefore, dealt mainly with published reports and with contributed data, resulting in a summary of identifying characters which the workshop considered useful and reliable.

Once the young tuna has acquired the full complement of spines and rays in all the fins, complete ossification of all the vertebrae, and the relocation of the anus near the origin of the anal fin, it is generally considered a juvenile of the species. Certain characters such as the full number of gill rakers, however, develop much later, when the juvenile has attained a length of 40 or 45 mm SL. If we consider juveniles to include all sizes up to the time of full gonad development signified by initial spawning, the size range of the juvenile stage would extend from about 13 mm SL to 700 mm FL (fork length) in *T. albacares* (Yuen and June, 1957) and to 860 mm FL in *T. alalunga* (Otsu and Hansen, 1962). For the purpose of clarifying species identification of the young, however, individuals beyond 200 mm SL need not be included. The term juvenile, as used here, thus refers to tunas between 13 and 200 mm SL.

EVALUATION OF CHARACTERS

The greatest difficulty in identifying juveniles of *Thunnus* is that the most useful characters are located internally. Except for the flattened first elongate haemal spine in *T. alalunga*, there is no single character that is peculiar to each of the species; but by using a combination of characters it should be possible to identify most of the other species. A summary of the most useful characters discussed is listed in Table 5.

The size of juvenile at which each of the characters can be observed is listed also. Those characters whose usefulness in the early juvenile stages has not been shown conclusively are indicated by a question mark (?). The general formula of distribution of pterygiophores of the second dorsal fin has not been used before.

The counts and descriptions given for those characters listed with a question mark generally are those of the adults. These have not yet been substantiated for juveniles as well. Changes in the position of the first haemal arch with growth, for example, have been known to exist in other closely related fish such as the wahoo, *Acanthocybium solandri* (Matsumoto, 1967). This could be true of the tunas also.

Comparisons of body parts, particularly of orbit diameter, body depth at origins of the first dorsal and anal fins, preanal and postanal distances, and snout length, have not been investigated sufficiently in the past. The unavailability of specimens in sufficient numbers as well as the nonuniformity of body lengths (fork and standard) used have contributed greatly to this neglect. Acceptance of standard length as the standard measure of body length and publishing of actual measurements in the future should help in the accumulation of sufficient data for analyses. This has to be done by all workers in this field of study, since the juveniles are not easily taken in large numbers.

TABLE 5.—Characters for separating juveniles of *Thunnus* species.

Character	Useful on juveniles above	<i>Thunnus thynnus</i>	<i>Thunnus alalunga</i>	<i>Thunnus atlanticus</i>	<i>Thunnus obesus</i>	<i>Thunnus albacares</i>
First haemal arch	?	10	10	11	11	11
Ceratobranchial including angle	40 mm SL	17-20	15-16	12-13	15-16	15-16
Vertebrae	13 mm SL	18 + 21	18 + 21	19 + 20	18 + 21	18 + 21
Array of ¹ D ₂ pterygiophores between two adjacent neural spines	10 mm SL	1, 2, 2, 3, 2, 2, 1, 1	1, 1, 2, 2, 2, 3, 2, 1	1, 2, 2, 2, 3, 2, 1, 1	1, 2, 2, 2, 3, 2, 1, 1	1, 2, 2, 2, 3, 2, 1, 1
First prezygapophysis and position on haemal arch	?	15, 16, 17, high	15, 16, high	16, 17, low	15, 16, high	13, 14, low
Postzygapophysis near first prezygapophysis	?	Short, directed posterior	Short, directed posterior	Long, directed vertical or slightly anterior	Short, directed posterior	Long, directed vertical, some slightly anterior
First haemal spine	30 mm SL	Winglike at some stages	Extremely winglike	Winglike at some stages	--	--
Lateral line above base of pectoral fin	25 mm SL	Acute, nearly 90°	Obtuse	Obtuse	Obtuse	Obtuse

¹ D₂ refers to second dorsal fin.

DISCUSSION AND SUMMARY

T. thynnus below 25 mm SL can be separated from the other *Thunnus* species by the array of pterygiophores of the second dorsal fin, the last four positions containing 2, 2, 1, 1 pterygiophores; in *T. alalunga* the sequence is 2, 3, 2, 1, and in *T. atlanticus*, *T. obesus*, and *T. albacares* it is 3, 2, 1, 1. *T. thynnus* above 25 mm SL can be separated from all other *Thunnus* by the sharp angle (nearly 90°) which the lateral line follows near the base of the pectoral fin; in all other species this angle is obtuse. In juveniles above 40 to 45 mm SL, *T. thynnus* has the highest number of gill rakers on the ceratobranchial, including that at the angle (Potthoff and Richards, 1970).

T. alalunga below 30 mm SL can be separated from other *Thunnus* species by the distribution of pterygiophores of the second dorsal fin. Above 30 mm SL, *T. alalunga* is the only species whose first elongated haemal spine is flattened laterally and appears extremely winglike.

T. atlanticus as small as 13 mm SL can be separated from other *Thunnus* species by its distinctive precaudal and caudal vertebral counts. It is the only species having 19 precaudal and 20 caudal vertebrae. Above 40 to 45 mm SL, this species can be separated from the others by the low (12-13) gill raker count on the ceratobranchial (Potthoff and Richards, 1970), in addition to the vertebral formula.

T. obesus and *T. albacares* are the only two species that cannot be distinguished from each other on the basis of internal characters. Comparisons of body parts, i.e., orbit diameter, body depth or preanal and postanal distances, may have to be used.

ACKNOWLEDGMENTS

We thank John C. Marr, former Area Director, BCF Biological Laboratory, Honolulu, who originated the idea of the workshop; Richard S. Shomura, former Acting Area Director of the same Laboratory, who continued with the orig-

inal idea and organized the workshop; and the BCF Biological Laboratory, Honolulu, Hawaii, for providing laboratory space and facilities. The workshop was supported entirely by the Bureau of Commercial Fisheries (now National Marine Fisheries Service).

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Precisely deactivated adsorbents applied to the separation of chlorinated hydrocarbons

The active sites on silica or alumina adsorbents do not all have the same energy of interaction with a given solute species. The most energetic sites must be occupied (masked) with a molecular species that is not transported appreciably by the eluting solvent if the adsorption isotherm is to be reasonably linear in the range of solute concentration experienced during the separation. Water and less frequently, ethylene glycol have been used to occupy the most energetic sites which lowers R_F values and reduces tailing of solute bands. The degree of deactivation is specified by the weight percent of water added to the adsorbent. The method described here is applicable to adsorbents usually deactivated with water (silica gel, magnesia, alumina and Florisil) and involves the equilibration of the activated adsorbent with a solution of a strongly adsorbed material in an appropriate solvent. The degree of deactivation can be specified by the composition of the deactivating solution. Elution must be performed only with solvents incapable of removing the strongly adsorbed species from the adsorbent bed.

Silica gel and alumina adsorbents for the chromatography of molecular species which are extremely non-polar such as polychlorinated biphenyls (PCBs) and DDT and its metabolites (DDTs) must be very active. Columns for the separation of chlorinated hydrocarbons from interfering biological materials prior to gas chromatography and columns for the separation of PCBs from DDTs must both be of Brockmann Grade I¹. However, the latter columns must be considerably more active and more reproducible than the former.

Experimental

Alumina columns. Due to its high column loading capacity, alumina has shown itself to be the best adsorbent for the separation of chlorinated hydrocarbons from biological materials prior to gas-liquid chromatography (GLC). Alumina (Baker No. 0536) is first activated at 400° for 4 h or longer and then forced into equilibrium with a 1% methanol in benzene solution. This is accomplished by the passage through a column of the adsorbent of 1.1 ml of deactivating solution per gram of alumina. The minimum amounts of solution necessary to deactivate columns having activities different from the one used in this example can be read from Fig. 1.

The adsorbent can be stored, covered by the deactivating solution, for several months in a tightly stoppered flask without change in its activity. Separation of chlorinated hydrocarbons from lipids is accomplished on a 5-mm diameter, 75-mm long column (a disposable Pasteur pipette 14.5 cm long plugged at the bottom with glass wool) containing 1.7 ± 0.1 g of alumina. The adsorbent is slurried into the column with deactivating solution, packed by vibration, and rinsed with 3 ml of hexane. Lipid samples as large as 45 mg extracted with acetone-hexane (50:50) from plankton and fish have been satisfactorily cleaned up for GLC with electron capture detection. However, sample size should be restricted to 15 mg of extractable lipid to guarantee that the column is not overloaded. The extract should be taken to dryness under vacuum to remove all traces of acetone. The concentration step should be performed at or below room temperature to minimize the volatilization

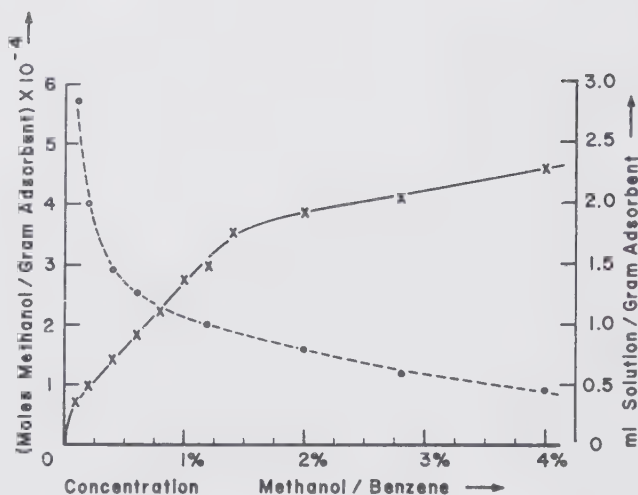


Fig. 1. The solid curve is the adsorption isotherm of methanol on Baker No. 0536 alumina from benzene solution. Isotherms were measured by frontal analysis with eluate fractions analyzed with GLC (DEGS column at 70° with thermal conductivity detection). The dashed curve and right-hand ordinate refer to the volume of methanol/benzene solution required to deactivate 1 g of alumina.

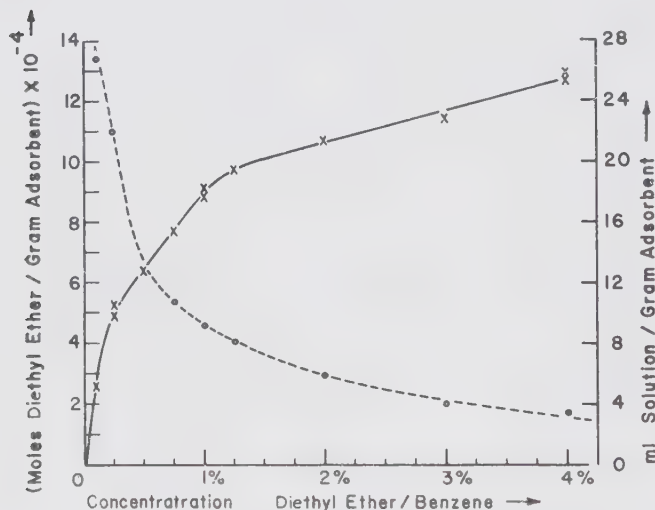


Fig. 2. Solid curve: The adsorption isotherm of diethyl ether on M.C. & B. SX-144-6 silica gel from benzene. Dashed curve and right ordinate: The volume of diethyl ether/benzene solution required to deactivate 1 g of silica gel.

of the pesticide residues. Complete recovery of PCB, polychlorinated naphthalenes, BHC, lindane, heptachlor, aldrin, heptachlor epoxide, dieldrin, endrin and DDT and its related compounds and metabolites can be expected in the first 3.5 ml of *n*-hexane. Short lengths (4 cm) of polytetrafluoroethylene tubing having 5-mm I.D. and 1-mm wall thickness are useful for coupling volumetric pipettes to the columns.

Silica gel columns. The separation on silica gel of the DDT metabolite, DDE, from the PCB isomer which interferes with it on most GLC columns is a very difficult task. The activity of silica gel reaches a maximum value at an activation temperature

of 185°. Silica gel activated at this temperature and used without deactivation exhibits an excessively small R_F value for DDE of about 0.015 with *n*-hexane as solvent. SNYDER AND REINERT² have utilized silica gel activated at 200°. This material is less active than the maximum possible and provides a reasonable R_F (DDE) of about 0.08.

A method that has shown itself to be reliable in our laboratory and which yields columns having $R_F(\text{DDE}) = 0.08$ consists of equilibration of silica gel (M. C. & B.* SX-144-6 activated at 180°) with a solution of 0.5 % diethyl ether in benzene. This is accomplished by the passage of the solution through the column until the ether concentration in the eluate equals that of the feed solution (12 ml of the solution per gram of silica gel is required, see Fig. 2 for minimum amounts of solution for columns having more or less activity). The column is then rinsed with 5 ml of hexane per gram of adsorbent to remove the benzene. A column having 4-mm I.D. and 230-mm length separates PCB in the first 10 ml of *n*-hexane. The DDTs are eluted with 5 ml of the 0.5 % diethyl ether in benzene solution. After a 10 ml *n*-hexane rinse the column is ready for re-use. Reproducibility can thus be enhanced by the use of the same column for standard and unknown solutions.

Discussion

If the eluting solvent removes some of the deactivating material from the column the adsorbent will become more active as the elution proceeds. Solute bands will be skewed and the retention volumes of the solutes will not be reproducible. Five consecutive *n*-hexane elutions from 1 % methanol/benzene deactivated alumina and from 0.5 % diethyl ether/benzene deactivated silica-gel yielded symmetric solute bands and constant retention volumes for various solutes for each series of consecutive elutions. Therefore, solvent activation of the adsorbents did not take place to a measurable extent.

If the adsorption isotherms of other substances on silica gel exhibit the abrupt change in slope found for diethyl ether at 5×10^{-4} mole/gram then columns not deactivated beyond this level will suffer from the effects of isotherm non-linearity if this level of surface coverage is reached during an elution. The strongly adsorbing sites responsible for the very steep portion of the diethyl ether adsorption isotherm on silica gel will also irreversibly adsorb impurities in the eluting solvent and reduce the activity of the column during the elution. On that portion of the isotherm where the slope is not as great, the tendency to irreversibly adsorb contaminants from the solvent was not so pronounced.

This work was supported in part by the Sea Grant Program under Grant No. GH-52 to the University of California, San Diego, Calif., U.S.A.

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Received March 20th, 1972

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Processing EASTROPAC STD Data and the Construction of Vertical Temperature and Salinity Sections by Computer

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ABSTRACT

During the EASTROPAC expeditions the STD (salinity-temperature-depth recorder) was established as the principal instrument for obtaining detailed profiles of temperature and salinity to depths exceeding 1,000 m. The STD system recorded data in digital form on magnetic tape and required computer processing to provide accurate temperatures and salinities at 1-m intervals for each hydrographic station.

Procedures for processing STD data from pre-processed digital logger tapes are described. Also included is a discussion of processing temperatures and salinities from the STD analog charts or from Nansen cast data when the digital data logger was not operative. Essential calibration of STD data from Nansen cast data is outlined. Finally, a computer program which prepares a final, annotated STD tape, with corrected temperatures and salinities, is described in great detail.

Another computer program was developed to provide for the EASTROPAC Atlas representative vertical sections of temperatures and salinities extracted from the final STD tapes. Details of computer methods employed to analyze and contour STD data are presented, and they are followed by an outline of computer requirements and program limitations.

The STD provided many detailed profiles along cruise tracks in the eastern tropical Pacific with an accuracy approaching those taken by Nansen casts; but it created new problems in processing oceanographic data. The problems, their solutions and recommendations are presented for those who may benefit from many months of processing STD data from EASTROPAC cruises.

INTRODUCTION

The EASTROPAC expeditions (1967-68) to the eastern tropical Pacific have provided the most extensive and continuous coverage of oceanographic and meteorological conditions

ever obtained. Three multi-ship survey (summer and winter) cruises, linked by single-ship monitor cruises, probed the ocean depths with an electronic STD¹ (salinity-temperature-depth

¹ The Appendix contains a brief description of the STD and its operation.

recorder) at unprecedented frequency. Six research vessels from the United States occupied stations which established the STD as the principal instrument for obtaining temperature and salinity data. The STD stations along the major cruise tracks, identified in EASTROPAC Information Papers 6, 8, 9, and 10 (Longhurst 1967, 1968, 1969a, and 1969b) and described briefly in the next section, have provided oceanographers with data of such a high degree of accuracy and vertical resolution that the microstructure of water masses in the eastern tropical Pacific could be examined in greater detail than was possible heretofore with conventional bathythermograph or Nansen cast data.

OBSERVATIONS

During the EASTROPAC cruises STD casts were completed from one side of a research vessel and followed by a Nansen cast from the opposite side for all primary stations on which complete hydrographic and biological observations were made. This procedure provided Nansen bottle temperatures and salinities, at 12 depths for 500-m casts and up to 20 depths for 1000-m casts, to compare with STD data. The STD analog profile of the water column (Fig. 1) was used at each station for determining the desired placement, relative to the thermocline, of Nansen bottles on the cable.

EASTROPAC stations were occupied at regular intervals along lines of longitude of various lengths between lat 20° N and 20° S. Stations were also occupied along diagonals and east-west lines connecting the major lines of longitude. The stations were designated A, B, and C, depending upon the types of observations made and the depths obtained. In most cases, stations were occupied every 20 nautical miles in the following order: A, C, B, C, A, C, B, C, etc. Between lat 5° N and 5° S, an additional "C" station was occupied between an "A" and "B" station. Characteristically, a 1000-m STD cast was made on all "A" stations, a 500-m cast on all "B" stations, and either a 300-m XBT (expendable bathythermograph) or 300-m STD cast on all "C" stations. In an area of special interest or between major lines of longitude, a 300-m or 500-m STD cast was made.

Lowering rates of the STD sensor were established to minimize irregular salinity val-

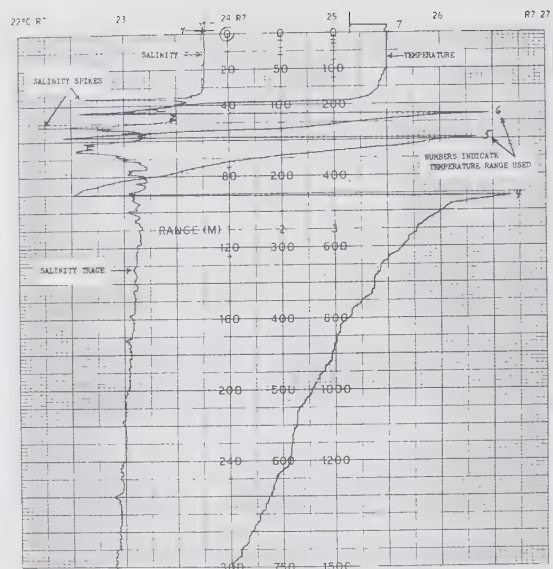


Figure 1.—Reproduction of original STD analog trace made on EASTROPAC Cruise 20, Station 208, on May 15, 1967 (lat 02°25' S, long 104°56' W). The salinity trace (on the left) shows "spikes" in the thermocline where temperature trace (on the right) shows rapid decrease with depth (frequent switch-back of temperature trace).

ues. This was especially important through the thermocline where the STD sensor could not compensate quickly to the effect of rapid temperature changes on conductivity. Through experimentation, at various drop rates, satisfactory results were obtained at 35 m/min through the thermocline to approximately 200 m, and at 75 m/min at deeper levels.

DATA PROCESSING

Because the STD system was designed to record data at high rates in digital form on magnetic tape, processing of the digital data logger (DDL) tapes has been carried out by computer. The initial data processing of approximately 38 STD field tapes, collected during EASTROPAC, into 17 tapes (hereafter called intermediate tapes) of smoothed profiles of temperature and salinity at 1-m intervals was described by Jones (1969). The sections which follow discuss in detail the procedures, both manual and automated, which have evolved over many months of techniques developed for processing STD data from intermediate tapes into

corrected final data tapes, and thereafter, the construction of vertical sections of temperature and salinity.

Processing Data From a Digital Data Logger

The STD system is designed to be used with a digital data logger. The data logger records the data accurately and eliminates the tedious process of picking off inflection points of temperature and salinity from the analog trace and interpolating between points at 1-m intervals. If, for example, the STD probe is lowered to 500 m, the complete cast would consist of an STD tape record of depth, temperature, and salinity for each meter of depth extracted from the DDL tape, as well as a visual interpretation of the same data by means of an analog trace.

Computer printouts of the intermediate STD tapes have clearly shown that the ideal cast was rarely obtained. More commonly, the upper and/or lower few meters of data were missing on tape and occasionally half or nearly all of the data were missing. For this reason a computer program referred to as TAPEMOD was developed to fill in data at the missing levels. There were five types of corrections used in this program, depending on where and how much data were missing. They were designated by code as types 0 and 1 corrections for only a few surface and lower levels missing, types 2 and 3 for several lower and upper levels missing, and type 4 for the entire DDL record missing on tape. In a very few instances, anomalous data on tape had to be replaced. (This was done in a special section of the program.) Types 0 and 1 were internal corrections made by extrapolating temperature and salinity between two depths (specified on computer data control cards). Types 2, 3, and 4 were external corrections made by inserting data cards (containing temperatures and salinities) derived from an interpolation program. These corrections and the interpolation program will be discussed in greater detail in subsequent sections.

Processing Data From Analog Traces

On several EASTROPAC cruises a digital data logger was not used or it was inoperative

at least part of the time. In these situations the STD data were recorded only on the analog traces. Occasionally the entire STD system failed to operate so that Nansen casts provided the only data for determining temperatures and salinities. Fortunately, most of the STD data were recorded on tape in digital form and subsequently processed directly onto an intermediate data tape at 1-m intervals.

An analog trace of temperature and salinity vs depth was produced as the STD sensor was lowered (Fig. 1). Several points of inflection were manually picked off the temperature and salinity traces; these points were selected to describe adequately the temperature and salinity structure of that particular column of water. In the region of a sharp thermocline, particular care was needed in extracting data points. In this region, the temperature scale changes rapidly, which results in a nearly horizontal temperature trace compressed over a small change in depth. (Fig. 1 illustrates a typical sharp thermocline.) A data point was usually extracted at the top, midway through, and at the bottom of the thermocline. If the temperature gradient was not particularly severe, one or two additional data points were extracted in the thermocline.

The salinity trace in Figure 1 illustrates a feature called "spiking" which was frequently found in a sharp thermocline. This anomalous feature resulted when the STD sensor passed through a strong temperature gradient. This situation required reconstructing the trace by penciling in a revised profile line which either eliminated a single spike entirely or averaged adjacent spikes. Data at inflection points were then extracted from the penciled line. Depths, temperatures, and salinities extracted from each trace were subsequently punched onto IBM data cards. A computer program described in the following section used these data cards to interpolate between inflection points the depth, temperature, and salinity at 1-m interval.

The Interpolation Program

Prior to EASTROPAC the Inter-American Tropical Tuna Commission had developed a computer program to interpolate temperatures and salinities to standard depths. Because this program incorporated established mathematical

procedures for interpolating Nansen cast data to conform to typical profiles, it was adapted for use with STD data. A mathematical description of the interpolation scheme is presented by Forsbergh and Broenkow (1965). A general description of the interpolation program, as adapted for EASTROPAC, is as follows:

1. Depths, temperatures, and salinities extracted from STD analog traces or from Nansen cast data in the absence of STD traces are read into the computer from tape or card decks with one set of data and a header record for each station to be interpolated.
2. From information entered into the computer on control cards, the levels for which interpolation is to be performed are set up for each station.
3. Before the interpolation begins, thermosteric anomalies are computed for all of the levels for which the initial observations are entered. If there exists a subsurface maximum of temperature, the temperature profile (water column) is divided into three regions. Region 1 extends from the surface to the depth of maximum temperature or thermosteric anomaly. Region 2 lies between the depth of maximum temperature and the midpoint of the maximum temperature gradient in the thermocline. Region 3 includes all depths below the mid-thermocline depth. When no inversions exist in the mixed layer and the highest temperature is at the surface, the water column consists of Regions 2 and 3.
4. Temperature gradients are computed between successive pairs of temperatures from the surface to the lowest depth. The maximum temperature gradient is found and a depth, temperature, and thermosteric anomaly for the midpoint of maximum gradient is found by linear interpolation.
5. Interpolations at 1-m depth intervals of temperatures and thermosteric anomalies are computed for the upper and lower regions by a logarithmic equation. When a surface temperature and/or salinity is

missing or a subsurface temperature maximum exists, the apparent surface values are determined by logarithmic extrapolation.

6. After all temperatures and thermosteric anomalies have been interpolated, the potential density anomalies are computed from the interpolated thermosteric anomalies. Finally, the interpolated salinities (at 1-m intervals) are determined by an iterative computational procedure using a transformed potential density anomaly equation (sixth degree polynomial) where the salinity is the only unknown. The initial value of salinity is set at 35‰ for the iteration.

The interpolated data are punched on cards or put onto tape by program option. The computer output also includes a printer listing of observed and interpolated values of temperature, salinity, potential density and stability (variation of potential density anomaly with depth). In addition, profiles of temperature vs. depth and temperature vs. salinity are printed. The printer output provides quality control information for determining the acceptability of the interpolations.

Each set (station) of observed data is interpolated from the uppermost to lowest required depths, and the data written on the output tape before the program loops back to work on another set. Copies of this program (FORTRAN source language) and a detailed write-up of its operation are available at the National Marine Fisheries Service (NMFS), La Jolla, Calif.

Calibrating STD Data

The STD data interpolated at 1-m intervals and stored on the intermediate tape were calibrated at selected levels against corresponding data of the Nansen cast. Two levels were chosen for calibration, one at the surface and the other at approximately 400 m. The latter seemed to be sufficiently below the thermocline to eliminate anomalous "spikes" (see Fig. 1) which sometimes appeared on the analog traces where there were strong temperature gradients. Temperature and salinity differences between STD data and Nansen data were calculated at each level and plotted against a sta-

tion number. At the 400-m level, a running average of the differences was plotted (Figs. 2 and 3). From these plots correction factors were determined by the least squares method and punched onto each station identification card (described in the next section). Every temperature and salinity value recorded on the intermediate tape was modified according to the signs and magnitudes of the corrections. The anomalous surface temperature and sa-

linity values on tape were corrected in the TAPEMOD program to correspond to those obtained from the surface calibration curves.

Preparation of the Final STD Tape

During the development of the computer programs to process STD data it became apparent that data on the intermediate tapes for each cruise had missing temperatures and salinities at the top and/or bottom of most of the casts. In addition, small temperature and salinity corrections were needed to correct nearly all STD data so that they would be consistent with Nansen data. Therefore, it was decided to prepare a final STD tape which incorporated the temperature and salinity corrections and the missing data. Furthermore, for proper identification of each set (station) of data, time, date, and location annotations were required at the beginning of each data set. Procedures for obtaining corrections and missing data have been described in the previous sections. The remainder of this section will describe the preparation and format of a final, annotated STD data tape. The format of the STD final tape was developed through a coordinated effort of the EASTROPAC staff from the NMFS, La Jolla, and Scripps Institution of Oceanography. Representatives of the National Oceanographic Data Center, Washington, D.C., were consulted as to their requirements for archiving of STD data on magnetic tapes and their distribution.

The STD data for each station of a cruise consisted of a separate file on the tape. Each tape contained as many files as there were usable STD casts taken during a cruise. The number of files (stations) of STD data was not recorded on the tape. However, EASTROPAC Information Papers No. 6, 8, and 9 indicate which stations have STD data on tape and the lowest depth reached on each cast.

Each file of STD data consists of three computer records written on tape in hyper-density (800 bits per inch) as described below. A partial computer printout of STD data for a station from the final tape is shown in Figure 4.

1. Record one contains, in binary-coded-decimal (BCD) form, the latitude, longitude, date, time (at beginning of STD cast) and

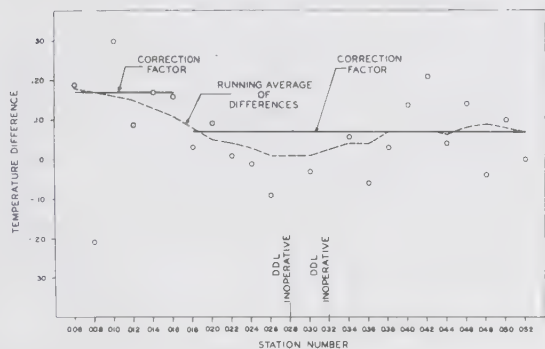


Figure 2.—Plot of temperature differences between digital data logger (DDL) and Nansen data at approximately 400 m. A correction factor, derived from a running average of nine values of temperature difference, is applied to the DDL temperatures. In this plot a correction of $+0.17^{\circ}\text{C}$ is applied for stations 006 to 016 and a correction of $+0.07^{\circ}\text{C}$ for stations 018 to 052.

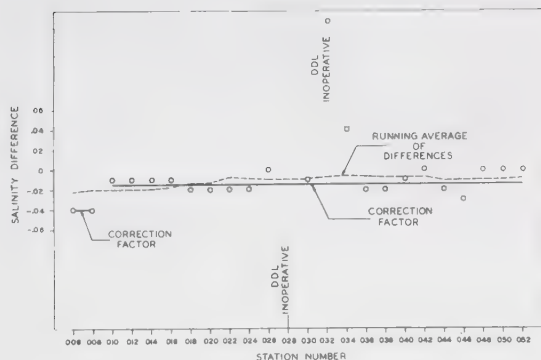


Figure 3.—Plot of salinity differences between digital data logger (DDL) and Nansen data at approximately 400 m. One or more correction factors are derived from a running average of nine salinity difference values and applied to the DDL salinities. In the above plot, a correction of -0.040‰ is applied for stations 006 to 008 and a correction of -0.015‰ for stations 0170 to 052.

the depths between which modifications or additions were made.

2. Record two consists of two binary words giving, in order, the EASTROPAC station number followed by the lowest depth to which a usable cast was recorded.
3. Record three contains, in binary format, all depths, temperatures and salinities, in sequence, for each meter of depth from the surface to lowest depth recorded.

The computer program, TAPEMOD, which prepares a final tape, consists of three parts which run in sequence through each file of data from the first station to the last in a cruise. The first part of the program reads in program control data cards which designate the stations and inclusive depths that require modifications or additions. The first set of control cards contains, in ascending order, the station numbers and types of correction for each station. These are followed by a second set of control cards specifying the upper and lower levels to which the corrections are to be applied. Following these two sets of control cards is a set of station identification cards. There is a card for each STD station containing cruise number, station number, date, time, latitude, longitude, and the temperature and salinity correction factors. The first part of the program is concluded when the major program loop is entered and the STD data on the intermediate tape for a station is stored in the computer's memory.

The second part of TAPEMOD consists of determining from control data which type of modification, if any, is to be applied for a station to fill in missing data or replace existing data. Five types of corrections were described earlier; each is designed to perform one of the following functions:

1. Insert missing temperatures and salinities from input data at one or more 1-m levels from the surface downward for cases where the top of the mixed layer is not isothermal and/or isohaline. In all isothermal and isohaline cases, the program automatically fills in missing data upward from the first valid depth with data.
2. Interpolate internally missing temperatures and salinities between two prede-

ignated (by control cards) depths where the desired temperatures and salinities have been obtained from STD analog traces or Nansen cast data. This type of correction can be made between any two depths of the STD cast.

3. Insert missing temperatures and salinities which have been interpolated externally between given depths. These data are read into the program from tape or cards which were generated by the interpolation program.
4. Replace or insert an entire cast of temperatures and salinities which have been interpolated at 1-m intervals externally from data read at inflection points off the STD analog traces or from Nansen bottle data. In this type of correction the STD data on the intermediate tape were found to be in error over nearly all the cast.

The second part of TAPEMOD terminates with an application of a single valued correction for each temperature and another for each salinity—the values of which are predetermined and applied at all depths. If no corrections are to be applied for a station, the appropriate columns on the station location card are left blank.

In part three of this program, the salinity profiles are smoothed for a second time. The first smoothing of temperature and salinity profiles is accomplished when the intermediate tape is prepared (Jones, 1969). Additional smoothing of salinity profiles is accomplished in TAPEMOD using a step function filter developed by Taft and Jones at the Scripps Institution of Oceanography. The filter consists of a tapered running mean which smooths out the peaks (spikes) on the salinity profile and leaves the end points of each spike with very little alteration. Several filters were tested with EASTROPAC STD data.

Finally, the completed and corrected STD cast of data is written on the final tape in three records as described above. The top and bottom 50 m of data are listed by computer together with the station annotation record as shown in Figure 4. These listings serve as quality checks for the computer processing.

The program repeats the steps described above station by station until an entire cruise

STATION NO. 20 208 303 METERS IN DEPTH
 FOR 15- 5-67 AT 900L .LAT. -225R S LONG. 104560 MAN-INTRP. 07C ON. FINAL TAPE
 VALUES INTERPOLATED AT 1 METER INTERVALS

DEPTH (M)	TEMP (°C)	SALN (0/00)	DEPTH (M)	TEMP (°C)	SALN (0/00)	DEPTH (M)	TEMP (°C)	SALN (0/00)	DEPTH (M)	TEMP (°C)	SALN (0/00)
0	25.34	35.213	1	25.34	35.213	2	25.34	35.213	3	25.34	35.213
4	25.34	35.213	5	25.30	35.211	6	25.29	35.211	7	25.28	35.211
8	25.27	35.211	9	25.30	35.211	10	25.37	35.211	11	25.39	35.211
12	25.40	35.212	13	25.39	35.212	14	25.39	35.212	15	25.40	35.213
16	25.40	35.214	17	25.39	35.214	18	25.38	35.215	19	25.34	35.214
20	25.36	35.214	21	25.37	35.214	22	25.35	35.213	23	25.33	35.212
24	25.31	35.211	25	25.30	35.211	26	25.29	35.211	27	25.28	35.207
28	25.27	35.201	29	25.26	35.164	30	25.23	35.182	31	25.19	35.170
32	25.13	35.163	33	25.06	35.165	34	24.86	35.170	35	24.65	35.163
36	24.45	35.151	37	24.04	35.119	38	23.43	35.132	39	23.17	35.127
40	22.70	35.123	41	22.56	35.123	42	22.42	35.124	43	22.28	35.119
44	22.14	35.111	45	22.00	35.099	46	21.89	35.106	47	21.77	35.114
48	21.66	35.114	49	21.55	35.102	50	21.44	35.089			
253	12.28	34.885	254	12.27	34.885	255	12.26	34.883	256	12.26	34.881
257	12.25	34.883	258	12.24	34.879	259	12.23	34.877	260	12.22	34.877
261	12.21	34.877	262	12.21	34.878	263	12.20	34.879	264	12.20	34.880
265	12.20	34.882	266	12.19	34.883	267	12.19	34.883	268	12.18	34.884
269	12.17	34.884	270	12.16	34.884	271	12.16	34.884	272	12.15	34.884
273	12.14	34.884	274	12.13	34.883	275	12.12	34.883	276	12.11	34.883
277	12.11	34.883	278	12.10	34.883	279	12.10	34.882	280	12.09	34.882
281	12.06	34.881	282	12.05	34.881	283	12.04	34.881	284	12.04	34.880
285	12.04	34.881	286	12.03	34.878	287	12.04	34.877	288	12.03	34.875
289	12.02	34.873	290	12.01	34.872	291	12.00	34.871	292	11.98	34.870
293	11.98	34.869	294	11.97	34.868	295	11.96	34.868	296	11.93	34.867
297	11.91	34.863	298	11.91	34.870	299	11.90	34.871	300	11.90	34.873
301	11.90	34.874	302	11.88	34.875						

Figure 4.—Partial computer printout of STD data for Cruise 20, Station 208, on May 15, 1967 (lat 02°25' S, long 104°56' W) as compiled on magnetic tape. The upper and lower 50 m are printed for an initial data quality check. The above calibrated data and analog data (Fig. 1) were taken simultaneously.

of STD data has been processed. As soon as a final tape has been written it is ready for use in constructing vertical sections of temperature and salinity. Vertical sections for selected stations (up to 54 stations per section) are constructed by a computer program described in the next section. There are available for reference at the NMFS Southwest Fisheries Center, La Jolla, complete 1-m listings of temperature and salinities for each station and all cruises. Listings of STD data for selected stations from the final magnetic tape can be obtained also for a small computer charge.

CONSTRUCTION OF VERTICAL SECTIONS BY COMPUTER

The Computer Program

A computer program was developed to provide a rapid and accurate means of constructing vertical cross sections of sea temperatures and salinities (Figs. 5 and 6) observed at stations along cruise lines. Although this program was designed to use STD data recorded on magnetic tape, other versions also are being used on the EASTROPAC Project to contour other physical, biological, and chemical data obtained

from Nansen bottle samples. The entire program is written in FORTRAN language used for compilation into computer language by the CDC 3600 computer. This FORTRAN language is compatible with the FORTRAN IV language used by other large scale scientific computers. The analyses are generated by computer, but the drawing of contours is done by a CalComp Plotter.

The program consists of a main part with the acronym VACOST (vertically analyzed contours of oceanographic salinities and temperatures), and two subprograms referred to as CONTRA and CONTRB. In VACOST temperatures and salinities for selected stations are read from magnetic tape into the computer's memory. The STD data are arranged into four two-dimensional arrays by station and depth. The four arrays consist of sets of temperatures and salinities which are subdivided into two arrays: one array contains temperatures or salinities for 0- to 300-m depths at 2-m intervals; the other array contains temperatures or salinities for depths from 300 to 500 m or to 1000 m at 5-m intervals. The temperature data are contoured from two arrays first while salinity data are temporarily stored on a computer disk file. After the temperature contour

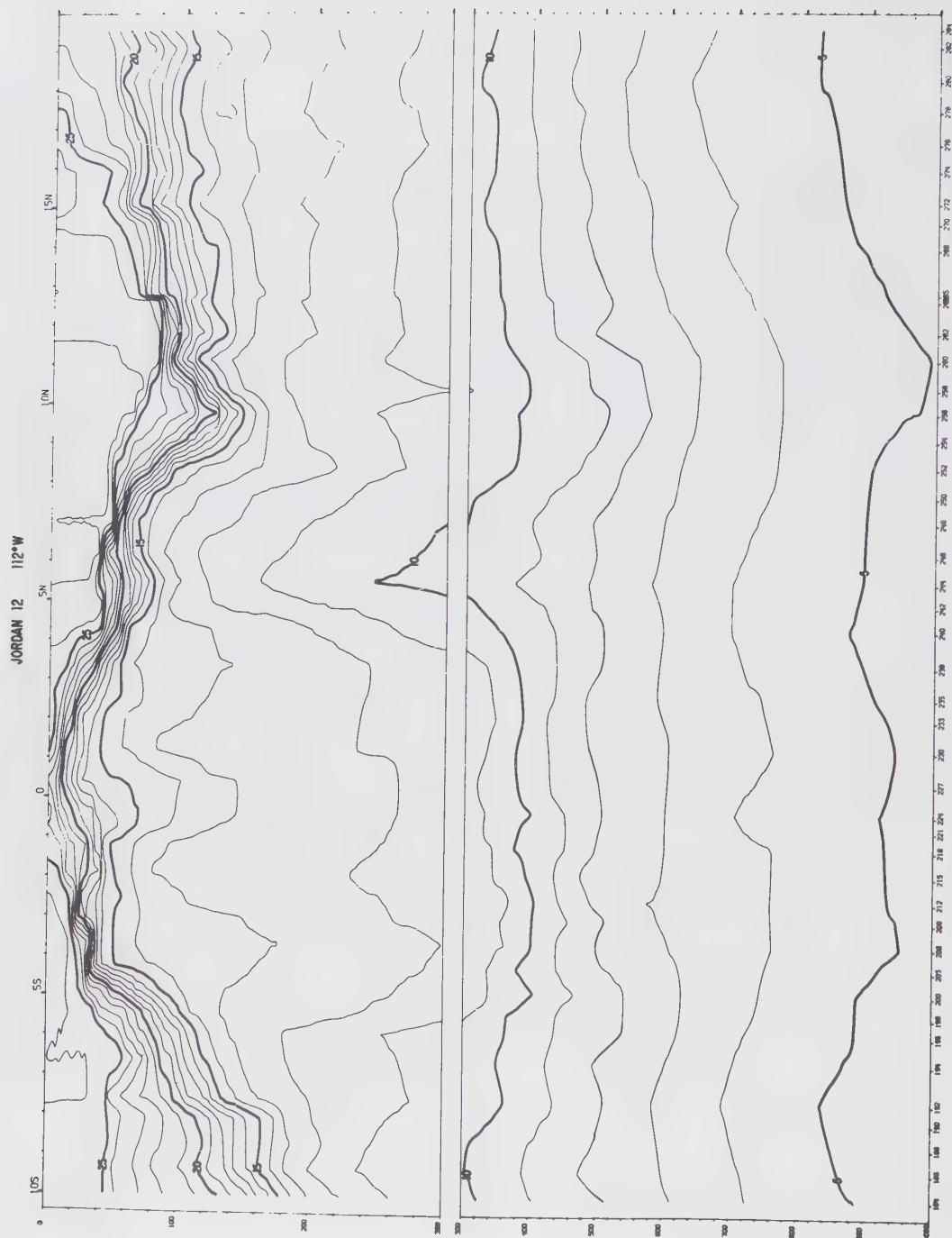


Figure 5.—Computer-drawn vertical section of temperature from STD data taken aboard the National Marine Fisheries Service RV *David Starr Jordan* on EASTROPAC Cruise 12 along long 112° W from 20° N to 10° S during February 1967. Isotherms, chart borders, and labels were constructed in the computer and drawn by CalComp Plotter. A draftsman relabeled and widened every fifth contour.

JORDAN 12 112°W



Figure 6.—Computer-drawn vertical section of salinities from STD data taken aboard the National Marine Fisheries Service RV *David Starr Jordan* on EASTROPAC Cruise 12 along long 112° W from 20° N to 10° S during February 1967. Isotherms, chart borders, and labels were constructed in the computer and drawn by CalComp Plotter. A draftsman relabeled and widened every fifth contour.

analysis is complete, salinities replace the temperatures in the same data array. The computer's memory size limits the program to using not more than 54 stations of data during one run.

Once an array of data is properly stored the program transfers control to the subprogram CONTRB, where the contour analysis is performed. First, the locations of isotherms (1°C interval) for the 0- to 300-m and 300- to 1000-m sections are determined, and CalComp Plotter commands are generated and written on a plotter (magnetic) tape. Then in a second pass through the program, locations of contours of salinities (isosals at 0.1‰ salinity) are determined, and appropriate CalComp commands are stored on the plotter tape following those for temperature.

The location of preselected contours in an array of data is performed in the CONTRB subprogram by means of a search routine. The boundaries or edges of each array are searched to find the beginning of a contour (if one begins at an edge). The search is continued inward from the edges using a four-point data subset, i.e., the data in the array for two consecutive stations and two depths, until an opposite boundary is reached or the contour closes on itself. When the end point of a contour is found, the search continues throughout the array to determine if there are other contours with the same value. This procedure is continued until the locations of all selected contours have been found in the array. The contour search routine is described in more detail in the next section.

The specific location of a contour within an array of data is given initially in terms of grid-point values which are referenced by depth and station number. When a contour falls between two grid points, a linear interpolation is made to find the exact grid location.

Plotting the Contours

The construction of the isotherms and isosals is done mechanically by means of the CalComp Plotter whose commands for constructing the frame of the sections, and printing latitude and station numbers, are generated in subprogram CONTRA. The vertical sections are variable in length, depending on the number of stations used. For the EASTROPAC

Project the longest vertical sections have been drawn along specified meridians between lat 20°N and 20°S , and they are from 35 to 40 inches in length. Each vertical section is divided into two parts: the upper section consists of the contours from the surface to 300 m with a fixed vertical distance of 11.86 inches (scale: $10\text{ m} = 1\text{ cm}$); and the lower section of contours extends from 300 m to 1000 m with a fixed vertical distance of 13.79 inches (scale: $20\text{ m} = 1\text{ cm}$). There is a 0.6-inch break between the upper and lower parts of the section. The locations of stations are marked by ticks and numbers between the section break and along the base of the lower section.

The CalComp Plotter draws contours by receiving, in sequence from magnetic tape, the horizontal and vertical distances of points along a contour as measured from a predesignated origin which is located in the lower left corner of a vertical section. Since the plotter requires incremental distances between points in inches, transformations from grid distances to actual chart distances in inches are completed before the plotter tape is written. Because the stations are not uniformly spaced, the horizontal distances are also rescaled. All scaling and transforming of the contour locations are completed as soon as the grid locations of a single contour are found within an array of data points. The transformed locations of all contours having the same value are stored on the plotter tape along with plot commands before a contour with a different value is located.

In order to space the stations properly along the horizontal axis of each vertical section, the program requires information giving the distances between each station—for the EASTROPAC expeditions the horizontal distance is 60 nautical miles equal to 3 cm in distance. After reading STD data from tape, the computer reads in a set of data cards with the properly scaled distances between the stations used for a particular section. These distances are in inches; they are computed in another computer program which reads the latitude and longitude of each station from a station location card and computes the number of nautical miles and scaled distances in inches from one station to the next. (At a later date it may be possible to use the latitudes and longitudes as read from the first record of each station on the final STD

data tape to compute the distances between stations.) The input data giving distances between stations also contain the station numbers to be used to label the stations at the bottom of each vertical section. Also, the distances, in inches, between 5-degree-latitude marks are read into the program for scaling the 1-degree tick mark onto the section.

The Contour Search Routine

The description of the contour search routine which follows does not reveal every step in logic followed by the subprogram CONTRB in locating and following the path of a contour through an array of data. Rather, the general scheme, which is used repeatedly, is outlined in a descriptive form. It is not possible to determine from this description alone the program logic without reference to the computer program. However, the program logic is not unique, and it is possible to write another subprogram using a similar search routine as used in CONTRB—but with other variations in the search patterns through and around a cell.

It is important to note that this contour routine yields good results because: (1) a simple search and linear interpolation scheme is used in a manner which simulates that used by an analyst; (2) the search is very fast because no attempt is made to use high order polynomial curve or surface fitting, which does require considerable computer time; and (3) the array of data is completely controllable without any modification. When the data array is formed, the contour analysis consists only in finding the location of selected isotherms or isosals.

Each contour with a value (VC) is located within the array of M by N data points (Fig. 7) by the following computer program steps:

1. Set the value (VC) of a temperature or salinity contour and enter CONTRB subprogram with the location of the data array "V", the number of stations (M), and the number of depths (N) in the data array to be contoured.
2. Search the outer edges of the array for the crossing of the contour (VC). If no crossing can be found on the outer edges, continue to search around and inward toward the center until a crossing is found.

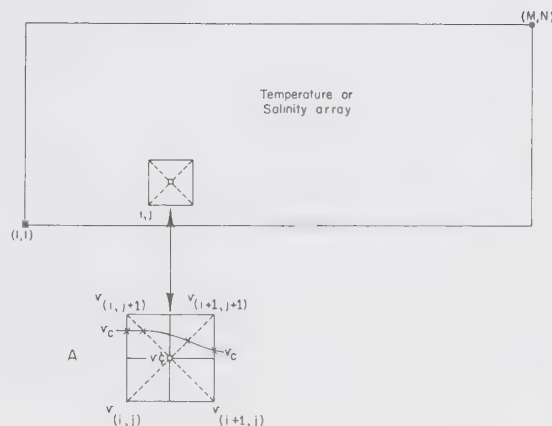


Figure 7.—A schematic diagram of a two-dimensional array of (M by N) data values of temperature or salinity formed in the computer prior to performing the contour analysis. A single cell (7A) within the array consists of data grid points for two adjacent stations and two consecutive depths. The location of a contour v_c within the cell is referenced from the lower left (i, j) coordinate. The (x) points represent crossing points at two edges and two diagonals passing through the center of the cell.

If no crossing is found, return to the main program. A check is made while moving through the array to assure that the boundaries are not being exceeded.

3. Once a contour crossing along an edge of a four point data subset (cell) between two adjacent stations is found, the search continues across the cell. The cell is divided into four equal sectors as shown in figure 7A; and the value at the center of the cell is found by

$$v_c^1 = \frac{1}{4} (v_{i,j} + v_{i+1,j} + v_{i,j+1} + v_{i+1,j+1})$$

where the subscripted (v) values represent data points of temperature or salinity at the four corners of a cell. By determining the edge of the cell through which a contour crosses, the sector of the cell into which the contour passes is marked. The proper indexing parameters for location are determined, and the next contour point is found by a linear interpolation along the diagonal from the nearest corner to the center of the cell (v_c^1). The sector entered is marked by placing a (1) in a location of the array (KK) reserved for keeping track of cells already entered.

This prevents running two or more contours with the same value through the same sector.

4. The next step consists of finding the next sector within the same cell through which the contour passes and the appropriate points of diagonal crossing. If the contour does not pass into a third sector of the cell, it passes through one of three other edges of the cell. Tests are continually made to determine whether the intercell movement continues or the contour passes through an edge. As the contour leaves one cell through an edge, it also passes into an adjacent cell; and the steps described above are repeated. Three or four location points are found for each contour within a cell.
5. The search routine continues from cell to cell until a boundary of the array is reached or the beginning of the contour is again reached, i.e. the contour closes on itself. The program control returns again to the main program where the value of the next contour to be found is assigned and control returns again to CONTRB.
6. Before the location points of each contour are written on the plotter tape with appropriate plotter commands, the x (horizontal) and y (vertical) points along each contour are rescaled from grid values to inches from the plot origin. Finally, a running three-point smoother (with central point weighting) is applied to remove small irregularities which may be imposed on contours by not having a continuous field of data.

The program also prints out in an array the values of temperatures and salinities used during the contour analyses (optional).

Computer Requirements and Restrictions

1. Size and type: A medium or large-scale scientific computer similar to the CDC 3600 with a 32,000 word or greater memory core is required.

2. Source language: FORTRAN-63 for the CDC 3600 or a compatible FORTRAN IV language is used. (It may be necessary to modify some FORTRAN statements if FORTRAN IV is required as a source language.)

3. Tape drives: To compile the FORTRAN source program into machine language, two or more tape drives are used. At the time of execution, one magnetic tape drive is required to store CalComp commands and contour data points, and one scratch tape or disk file is used to store salinities.

4. Output equipment: A CalComp (30-inch drum) incremental (resolution: 100 increments/inch) Plotter, model 723, a tape drive, and a converter unit are required. Computer printer is needed to list out the temperatures and salinities which are being contoured. (An array format is optional.)

Computer Program Data Limitations

1. Core memory size must be 32,000 words or greater.
2. The product of the two dimensions of a data array times four must not exceed 32,000 because of a logic routine used in CONTRB for contour search.
3. The width of a vertical section cannot exceed 29.5 inches, but it may be any desired length.
4. A single analysis cannot use more than 54 stations of data because of memory size. However, two analyses can be run and spliced together by using the same station data for the last of one section and the first of the following section.

Library Subroutines Required

1. CalComp subprograms as described by California Computer Products, Inc. These subroutines are usually on the library tape at installations using the CalComp Plotter.
2. Standard Share type mathematic subroutines as: negative zero test, tape rewind and file skipping, tape read/write routines, print routines, arc tan function, minimum function of a number, and square root function.

Computer and Plotter Timing

1. To analyze contours at intervals of (1° C) for temperature and (0.1‰) for salinity from the surface to 1000 m for 50 stations requires approximately 4.5 min of computer time on the CDC 3600.
2. To plot the contour analyses in two separate plots for the dimensions described in 1 above requires 25 min of CalComp 30-inch plotter time.

CONCLUSIONS

The STD afforded oceanographers on EASTROPAC an opportunity of observing accurately and rapidly temperatures and salinities to great depths. Many oceanographic features only partially observed or understood from Nansen bottle or BT data have been documented and analyzed in great detail. The environmental conditions for the study of fishery ecology have become more definitive partly because of the STD.

While the STD has provided detailed profiles of water columns with an accuracy approaching that of Nansen cast data, it has created some new problems in processing, displaying and archiving oceanographic data. Most of the STD data processing and computer programming was begun in the last quarter of 1967, except for the initial computer work done by Jones (1969). The National Marine Fisheries Service, which was the principal funding agency during the EASTROPAC cruises, also provided most of the funds for data processing. Since processing large amounts of STD data on magnetic tape had never been carried out before, considerable expenditures in money and man hours have been devoted to the development of a procedure, involving both manual and computer techniques, which would insure accurate results with minimum personnel involvement.

Due to the enormous quantity of STD data collected from the ETP area and to unforeseen programming difficulties that eventually occurred, a great deal of manual effort as well as computer time was necessary to generate the data quality that was finally achieved. In the early stages, processing centered around program development followed by a quality inspection

of the field tape printouts. As processing progressed through each step, as outlined in preceding sections, various unforeseen difficulties were continually encountered requiring program revisions.

In order to minimize the manual effort and computer time required in processing future STD data, it is recommended that users of the STD adhere strictly to the following standard STD shipboard procedures and those described in Appendix A:

1. Lower sensor through the thermocline to about 200 m at a rate not exceeding 35 m/min.
2. To insure the STD has reached the desired depth, determine the actual depth obtained with the sensor by reading the frequency control panel. Inaccurate pen setting on the analog trace will produce inaccurate depth readings.
3. Allow a sufficient warm-up period, at least 15 min, for the sensor and recorder. This precaution will generally eliminate the recording of anomalous data in the surface levels.
4. Check the pen positions on the analog charts with bucket temperature and salinograph to insure proper initial positioning.

The procedures described in this paper are not unique and there may be other simpler or more complicated approaches; but wherever magnetic tape is used it is recommended that: (1) the tapes be of high quality; (2) large numbers of corrections should be programmed onto tape; and (3) the final STD data tapes should be well annotated and written with fairly uniform record lengths in a density mode of 556 bits per inch. Higher data density modes on magnetic tape may increase the cost of processing tapes when computer tape units are slightly out of adjustment.

Most of these recommendations were incorporated into the STD operating procedures before the EASTROPAC cruises were completed. However, it should be emphasized that if a digital data logger is not used and if operating procedures are not closely followed, the processing of STD data into useful information which can be profiled or contoured into sections will be very tedious and expensive. The STD

system is designed to be used with a digital data logger, and the correct use of the entire system will provide data tapes which are easy to process.

The initial set of vertical sections of temperature and salinity produced by computer are preliminary contour analyses from which the analyst can determine the accuracy of STD data for each station as related to adjacent stations. Large irregularities in the data are revealed graphically in the contour patterns of the vertical sections. The smaller irregularities and subtle changes in salinity can be examined in detail by reconstructing the vertical sections by computer using different contour intervals. Final computer-drawn vertical sections, which incorporate all desired changes in the STD data records, have been prepared for the EASTROPAC Atlas with only minor alterations being applied to the sections by a draftsman.

ACKNOWLEDGMENTS

The authors express their sincere appreciation for the encouragement and support given this work by the EASTROPAC Coordinators: Drs. Alan R. Longhurst and Warren S. Wooster. Without the guidance and generous assistance provided by Dr. Bruce Taft, an efficient and accurate STD data program would not have been possible. Dr. Mizuki Tsuchiya provided valuable assistance in evaluating the computer processed data, and he made many timely suggestions for improving the computer drawn vertical sections.

A special thanks to Ruth Opdycke who spent many tedious hours manually digitizing STD analog traces when the data logger data was

not available. Miriam Oleinik provided valuable assistance in programming STD corrections to be inserted onto the final STD data tapes; and C. M. Love, Editor of the EASTROPAC Atlas, greatly contributed to the design and format of the computer drawn vertical sections which appear in the Atlas.

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APPENDIX

OPERATION OF THE STD SYSTEM

By

RAYMOND E. SHUEY²

The Bissett-Berman, *in situ* Salinity/Temperature/Depth (STD) data system¹ is an ensemble of underwater sensors lowered by an armored single-conductor cable. The sensor's operating voltage is sent down the cable from the power supply section of the deck unit.

Salinity measurement utilizes an inductive probe to measure conductivity of which the final readout is in parts per thousand. Temperature is measured with a sensing element which is a fast-response, platinum resistance thermometer. Depth is measured with a platinum strain gauge.

Sensor output signals from these three measurements (frequency modulated) are multiplexed and sent up the single-conductor cable. A set of discriminators in the deck unit separate and convert the three FM signals into d-c analog voltages. The signals continue to a digital data logger (DDL) unit which scans all sensors and then records in computer-compatible format onto magnetic tape. The analog signals are plotted on an x_1 , x_2 , $-y$ recorder with salinity and temperature presented as functions of depth. The chart is its own function as it advances thus recording depth. Prior to making an STD cast, the following procedure is followed:

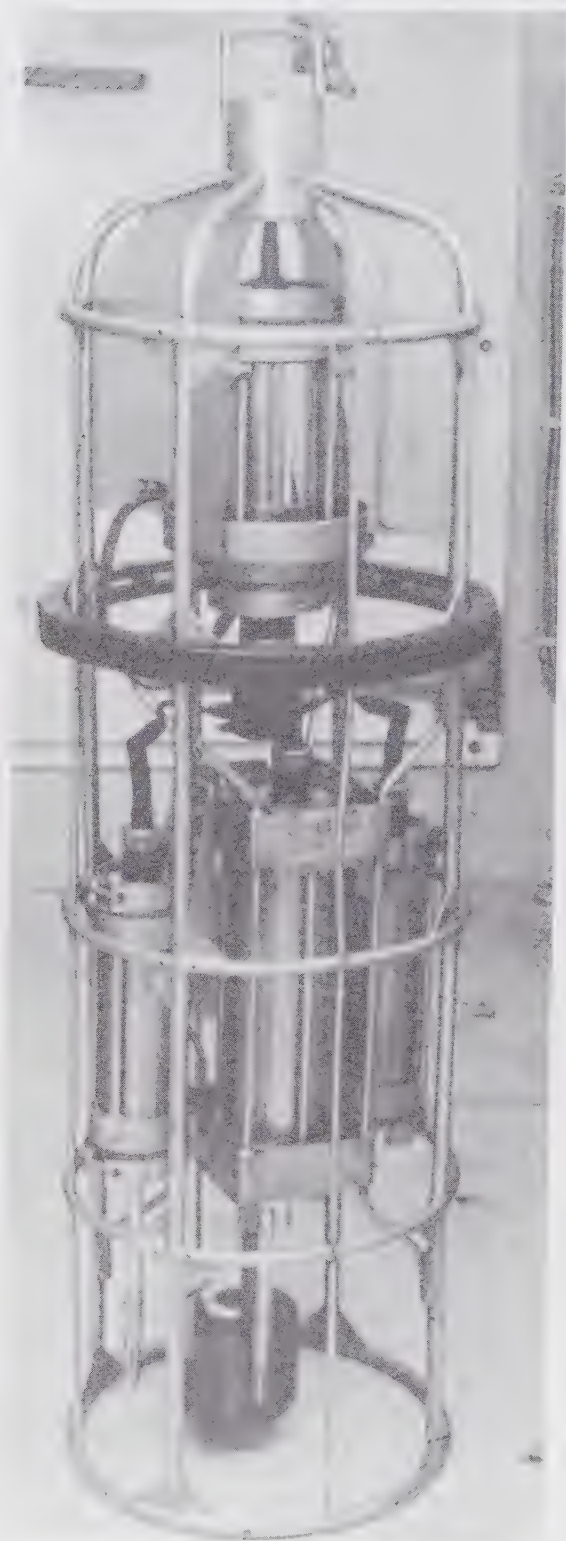
1. The recorder and sensor power-supply switches (Appendix Fig. 3) are turned on approximately 15 min in advance for warm-up.
2. The depth discriminator range is set to 0-300 m, 0-750 m, or 0-1500 m, depending on final depth desired.

3. Salinity-temperature-range switches are set to read surface values.
4. The station number is punched (inserted) on the DDL tape, and the sample interval is decided and set by a switch (sampling rate minimum of 100 m to a maximum of 16 sec).
5. The STD "fish" (Appendix Fig. 1) is lowered into the water just below the surface (Appendix Fig. 2) for a short soaking period.
6. The chart recorder (Appendix Fig. 3) is actuated with balance-motor switch.
7. The temperature pen is set on the surface line of the analog strip chart.
8. The salinity pen is set slightly above surface line to allow for pen crossing.
9. The data logger (Appendix Fig. 3) is switched on, and the cast is begun with the lowering of the fish at approximately 35 m/min.

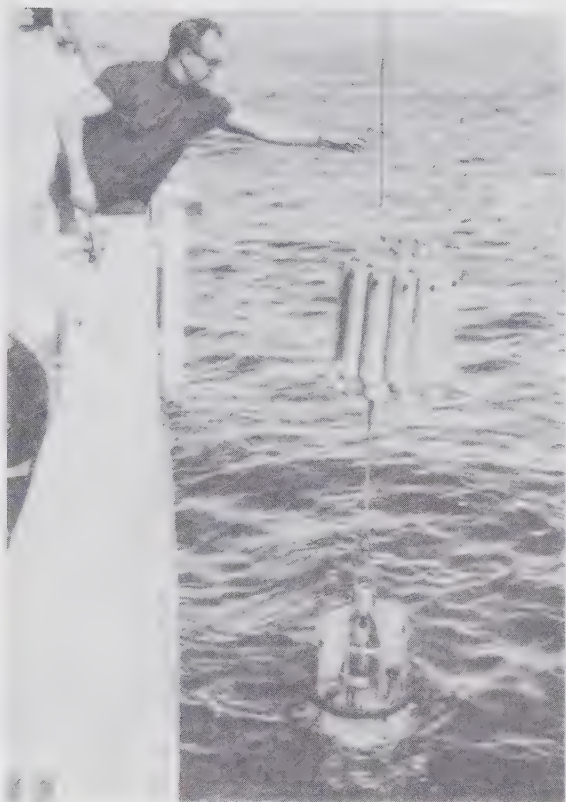
Until the fish is below the thermocline, the temperature-range switch, and in some instances the salinity-range switch, on the discriminators will need adjusting to avoid having the pens run off the scale. When the fish is below the thermocline the lowering rate may be increased to approximately 75 m/min since water is more stable. The deck unit usually includes an electronic frequency counter which can be used to monitor any of the three sensors. When the desired depth is reached, the DDL, balance motor, and recorder are switched off. The fish is retrieved at approximately 75 m/min while depth is monitored on the frequency counter.

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² The system is also referred to as the salinity-temperature-depth data acquisition system, Hytech Model 9006.



Appendix figure 1.—The STD probe unit or "fish" showing the protective cage for the temperature, depth, and salinity probes near the bottom. The probes lead into pressure cases which house the electronics. The pressure case near the top contains the multiplexing units which combine the signals and send them up the single-conductor cable.



Appendix figure 2.—Lowering the fish from RV *David Starr Jordan* to a soaking position prior to starting the cast. Robert Counts of the Southwest Fisheries Center steadies the cable just above a Niskin water sampler which is attached to the STD cable for a common lowering.

A

B

C



Appendix figure 3.—The STD electronic receiver unit (A), analog recorder (B), and digital data logger (C). The STD cast is monitored by frequency counters in (A) and the temperature-salinity tracer on the analog recorder. Magnetic tape mounted on the digital data logger unit records digitized signals.

DEVELOPMENT AND GEOGRAPHIC DISTRIBUTION OF THE ROCKFISH,
SEBASTES MACDONALDI (EIGENMANN AND BEESON, 1893),
 FAMILY SCORPAENIDAE, OFF SOUTHERN CALIFORNIA
 AND BAJA CALIFORNIA

H. GEOFFREY MOSER¹

ABSTRACT

The larval and juvenile stages of the scorpaenid fish, *Sebastes macdonaldi*, are described and illustrated. The sequence of ossification of bones and cranial spines in larvae is described in detail. *S. macdonaldi* appears to have the most southerly distribution of any species of *Sebastes* in the eastern north Pacific. The geographic distribution and seasonal abundance of *S. macdonaldi* larvae are discussed and compared with published information on the adults.

The genus *Sebastes* is represented by 65 species in the eastern north Pacific (Chen, 1971). Although all members of the genus are ovoviparous and have a planktonic larval stage, they exhibit a remarkable diversity in morphology, color, and mode of existence. They rank first in total numbers of fish landed annually by the California sport fishing fleet (Young, 1969) and are a major commercial resource (Heimann and Frey, 1968). Despite their obvious importance, information on the complete life histories of all but a few species is fragmentary or nonexistent. At present a complete life history series (embryonic, larval, juvenile, and adult stages) has been described for only a single eastern Pacific species, *S. paucispinis* (Moser, 1967); however, young-stage larvae attained from pregnant females have been illustrated for four species from central California (Morris, 1956), for nine species from the Pacific northwest (DeLacy, Hitz, and Dryfoos, 1964), and for 14 additional rockfishes from southern California and Baja California (Moser, 1967). Recently, Waldron (1968) has described the early larvae of *S. pinniger*.

Ahlstrom (1961, 1965, 1969) has shown that rockfish larvae are the third or fourth most

abundant kind of larvae collected annually in the plankton surveys of the California Cooperative Oceanic Fisheries Investigations (CalCOFI). Early juvenile rockfish, like the larvae, are pelagic but evade plankton nets easily and must be collected by other means. For example, some species are attracted to bright lights at night and can be dipnetted at the surface. Also, some species associate with floating objects (Hitz, 1961) and with drifting kelp (Mitchell and Hunter, 1970) and may be collected when these are brought aboard ship. Finally, pelagic juveniles occasionally appear in midwater trawl samples (Berry and Perkins, 1966; Lavenberg and Fitch, 1966). Demersal juveniles are common constituents of otter trawl catches in coastal waters.

Larvae of *S. macdonaldi* have such a distinctive melanophore pattern that a developmental series was established before it could be identified to species. The extreme southerly distribution of these larvae in the CalCOFI pattern provided a clue to their identity, since adults of *S. macdonaldi* have been collected farther south along Baja California than any other species of *Sebastes* (Chen, 1971). A comparison of intra-ovarian larvae from pregnant *S. macdonaldi* with the smallest individuals from plankton collections provided definitive evidence of the identity of the larval series. Juvenile stages critical

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to the completion of the developmental series were obtained principally from midwater and bottom trawls. These developmental stages are described herein, with special emphasis on the developmental osteology of the larvae. Also, the geographic distribution of the larvae in the CalCOFI area is presented and compared with the known distributions of juveniles and adults.

METHODS

Larvae of *S. macdonaldi* from 4 years (1953, 1960, 1965, 1966) of CalCOFI survey cruises were identified and counted. From these and selected other specimens, two developmental

series that encompassed the entire larval period were established. Larvae of the first series were measured with the ocular micrometer of a stereoscopic microscope to produce a table of morphometrics (Table 1) for comparison of body proportions of *S. macdonaldi* larvae with those of *S. paucispinis* and other species. This series also provided a framework for the descriptions of larval morphology and melanophore pattern. Larvae of the second series, cleared with a graded series of KOH-glycerin solutions and stained with Alizarin Red-S, were used to determine the sequence of ossification of bones and fin rays and to prepare a table of meristic characters (Table 2).

TABLE 1.—Measurements (mm) of larvae and pelagic juveniles of *Sebastes macdonaldi*. (Specimens between dashed lines are undergoing notochord flexion.)

Station	Body length	Snout-nose distance	Head length	Snout length	Upper jaw length	Eye diameter	Interorbital distance	Body depth	Pectoral fin length	Pelvic fin length	Snout to origin of anal fin	Snout to origin of pelvic fin
SIO 65-230	4.5	1.8	1.1	0.38	--	0.37	0.60	0.90	0.27	--	--	--
CalCOFI 6602-117.40	4.7	1.8	1.2	0.30	--	0.45	0.53	1.0	0.40	--	--	--
CalCOFI 6604-123.36	5.0	1.8	1.2	0.30	--	0.46	0.60	1.0	0.33	--	--	--
CalCOFI 6604-117.30	5.2	2.1	1.4	0.48	0.72	0.51	0.68	1.2	0.36	--	--	--
CalCOFI 6604-113.55	5.7	2.4	1.6	0.47	0.67	0.57	0.63	1.3	0.52	--	--	--
CalCOFI 6604-113.55	5.9	2.6	1.8	0.48	0.76	0.55	0.60	1.5	0.45	--	--	--
CalCOFI 6604-107.31	6.3	2.8	1.8	0.56	0.76	0.57	0.87	1.6	0.60	0.05	--	1.9
CalCOFI 6604-93.28	6.7	2.9	1.9	0.56	--	0.63	0.86	1.7	0.61	0.04	--	2.1
CalCOFI 6604-127.40	6.8	3.1	1.9	0.55	0.95	0.70	0.95	1.8	0.62	0.15	--	2.2
CalCOFI 6501-117.45	7.0	3.3	2.1	0.75	1.1	0.70	1.1	1.9	0.60	0.12	--	2.3
CalCOFI 5304-117.45	7.6	3.5	2.2	0.79	1.1	0.73	1.1	2.0	0.68	0.20	--	2.3
CalCOFI 6602-110.40	7.7	3.8	2.7	0.82	1.2	0.84	1.2	2.3	0.90	0.33	4.2	2.5
CalCOFI 6605-117.35	7.9	3.8	2.7	0.82	1.3	0.90	1.2	2.5	0.93	0.25	4.2	2.7
CalCOFI F-47-117.35	8.2	4.2	2.9	1.1	1.3	1.0	1.5	2.5	1.1	0.52	4.8	3.0
CalCOFI F-46-130.40	8.5	4.7	3.2	1.2	1.7	1.0	1.6	3.0	1.3	0.80	4.9	3.2
CalCOFI 5303-123.40	9.0	5.0	3.2	1.1	1.7	1.0	1.6	2.8	1.2	0.65	5.4	3.2
CalCOFI 6604-133.40	9.2	5.3	3.4	1.1	1.5	1.1	1.8	3.1	1.4	0.89	5.4	3.6
CalCOFI C-46-117.40	9.5	5.2	3.6	1.3	1.7	1.2	1.7	3.1	1.5	1.1	5.6	3.6
CalCOFI 6605-123.70	9.7	5.4	3.5	1.2	1.7	1.2	1.8	3.2	1.6	1.1	5.8	3.7
CalCOFI F-46-133.35	10.0	6.2	3.7	1.2	1.9	1.3	1.8	3.5	1.8	1.2	6.4	3.8
CalCOFI 6004-130.45	10.3	6.3	3.8	1.4	2.0	1.3	1.8	3.5	1.7	1.2	6.5	4.4
CalCOFI F-46-133.35	11.2	6.8	3.8	1.4	2.2	1.3	1.8	4.0	2.1	1.5	7.0	3.8
CalCOFI 5304-123.40	12.0	7.7	4.5	1.4	2.5	1.5	1.8	4.2	2.4	1.8	7.7	5.2
CalCOFI 6605-127.45	15.0	9.4	5.8	1.7	3.2	1.9	2.1	5.2	3.5	3.1	9.7	5.4
SIO 65-201	15.4	9.3	5.8	1.7	3.0	1.8	2.2	5.5	4.0	2.9	9.6	5.8
CalCOFI 6604-133.30	15.9	10.0	6.5	2.1	--	2.0	1.9	5.2	3.6	2.8	10.1	7.1
*SIO 61-299	22.6	14.0	8.4	2.7	3.6	2.3	2.5	7.5	6.7	4.8	14.7	9.3
*SIO 54-87	27.8	18.6	10.6	3.1	4.5	2.8	3.0	8.9	8.8	6.2	19.3	11.2
*SIO 69-232	29.2	19.1	10.8	2.9	4.8	3.2	2.9	10.0	9.8	6.5	19.9	11.7
*LACM 8821-9	32.7	20.7	11.8	3.2	4.9	3.6	2.9	10.1	9.7	--	20.8	12.2
*LACM 8821-9	34.5	20.9	11.8	3.2	5.2	4.0	3.2	10.5	10.6	7.7	21.4	12.7
*LACM 8821-9	38.8	25.0	12.8	3.2	5.4	4.0	3.5	11.7	11.2	8.3	25.6	14.4
*LACM 8821-9	40.2	26.8	13.0	3.5	6.1	4.2	3.6	12.0	12.2	8.5	27.4	15.2
*LACM 8821-9	44.4	30.2	14.0	3.8	6.4	4.7	3.8	13.2	13.2	9.2	31.2	16.2

* Pelagic juvenile.

TABLE 2.—Meristics from cleared and stained larvae of *Sebastes macdonaldi*.

Length (mm)	Primary caudal fin rays		Secondary caudal		Branchio- stegeal rays		Pectoral fin rays		Hypural elements		Dentary teeth		Anal fin rays	Dorsal fin rays	Pelvic fin rays		Vertebral centra	Neural spines	Haemal spines
	Superior	Inferior	Superior	Inferior	Left	Right	Left	Right	Superior	Inferior	Left	Right			Left	Right			
6.3	--	--	--	--	2	2	2	2	--	--	--	--	--	--	--	--	--	--	--
6.7	--	--	--	--	3	3	3	3	--	--	--	--	--	--	--	--	--	--	--
6.8	--	--	--	--	3	3	3	3	--	--	--	--	--	--	--	--	--	--	--
7.0	3	3	--	--	4	4	6	6	--	--	--	--	--	--	--	--	2	--	--
7.1	4	3	--	--	5	5	6	6	--	--	--	--	--	--	--	--	4	--	--
7.2	3	3	--	--	5	5	--	8	--	--	--	--	--	--	--	--	4	--	--
7.7	6	6	--	--	6	6	11	11	--	--	--	--	--	--	--	--	5	12	--
7.9	4	4	--	--	5	5	9	10	--	--	--	--	--	--	1-0	1-0	3	6	--
8.2	8	7	2	2	7	7	17	17	--	--	--	--	III-4	VII-0	1-3	1-3	24	20	7
8.5	7	7	--	--	6	6	15	15	--	1	--	--	--	--	1-3	1-3	18	18	6
8.7	8	7	--	--	7	7	16	16	--	--	--	--	--	--	1-3	1-3	18	19	6
9.2	8	7	2	3	7	7	19	18	--	2	--	--	--	VII-8	1-4	23	21	9	--
9.4	8	7	4	4	7	7	19	19	2	3	--	--	III-7	XIII-13	1-5	24	23	13	--
9.7	8	7	3	4	7	7	19	19	2	3	--	--	III-7	XIII-13	1-5	24	23	12	--
10.0	8	7	5	6	7	7	19	19	2	3	4	5	III-7	XIII-13	1-5	26	24	14	--
10.3	8	7	5	5	7	7	19	20	2	3	4	4	III-7	XIII-13	1-5	26	24	14	--
11.3	8	7	4	4	7	7	19	19	2	3	5	5	III-7	XIII-13	1-5	26	24	14	--
12.0	8	7	8	7	7	7	19	19	2	2	3	2	III-7	XIII-13	1-5	26	24	14	--
15.0	8	7	10	11	7	7	19	19	3	2	11	13	III-7	XIII-13	1-5	26	24	14	--
15.9	8	7	10	11	7	7	19	19	3	2	12	10	III-6	XIII-12	1-5	26	25	14	--

The critical pelagic juvenile stages were found in the fish collections of the Scripps Institution of Oceanography (SIO) and the Los Angeles County Museum of Natural History (LACM). Demersal juveniles were obtained from bottom trawl collections of the Southwest Fisheries Center, La Jolla, and the University of California at Los Angeles (UCLA), in addition to the two sources mentioned above.

Prior to the completion of notochord flexion during caudal fin formation, the body length is defined as the distance from the tip of the snout to the posterior tip of the notochord. After notochord flexion is completed the usual standard length measurement, the distance from the tip of the snout to the posterior margin of the hypural plate, is used. Morphometric changes in rockfish can be conveniently grouped into three phases that correspond to the stages of notochord flexion—one before flexion, one during flexion, and one after flexion is completed. These stages are separated in the morphometric table. Other terms used in this table are defined as follows:

Snout-anus distance = distance along midline of body from tip of snout to vertical from anus

Head length = distance from tip of snout to cleithrum

Snout length = distance from tip of snout to anterior margin of eye

Upper jaw length = distance from tip of snout to vertical from posterior margin of maxillary

Interorbital distance = width of tissue dorsal to eyes

Body depth = body depth at base of pectoral fin

Pectoral fin length = maximum length of rayed portion of fin

Pelvic fin length = maximum length of rayed portion of fin

Snout to origin of anal fin = distance along midline of body from tip of snout to a vertical from anterior end of anal fin

Snout to origin of pelvic fins = distance along midline of body from tip of snout to a vertical from pelvic fin base.

Terms used in the description of larval osteology conform largely to those used in recent studies of the osteology of adult teleosts (e.g., Harrington, 1955; Weitzman, 1962; Topp and Cole, 1968).

DESCRIPTION OF DEVELOPMENT

DISTINGUISHING FEATURES

Early-stage larvae of *S. macdonaldi* are characterized by a low number of melanophores (average of eight) in the series along the ventral midline of the tail. Of the 27 other species illustrated in the literature, only *S. paucispinis* larvae, with an average of nine melanophores in this series, approaches the low number of *S. macdonaldi*. Early larvae of *S. macdonaldi* are also characterized by their small, densely pigmented pectoral fins. Melanophores cover completely the blade of the fin, but are restricted to the inner surface of the fin base. Also characteristic is the series of melanophores which extends from the nape to the pectoral fin base. Such melanophores are not present on any other of the 27 other eastern Pacific species illustrated to date.

A fourth character of limited utility is the absence of melanophores on the dorsal surface of the tail. *S. macdonaldi* is one of the 16 eastern Pacific species illustrated to date which lacks this pigment, and can be immediately separated from the 12 species in which it is present. This character should be used with caution because the dorsal series of melanophores forms later than the ventral series, at about the time of yolk depletion (Moser, 1967; Waldron, 1968). Thus, prolarvae collected prematurely from the ovaries may not have yet developed their dorsal pigment series, and illustrations of this stage are not strictly comparable with those of larvae cultured to the point of yolk depletion.

GENERAL MORPHOLOGY

Larvae of *S. macdonaldi* are similar in general appearance to those of *S. paucispinis* (Moser, 1967). Larvae hatch within the ovaries at a length of 4 to 5 mm, and then are extruded from

the female. Newborn larvae have large heads with well-formed eyes and functional jaws (Figure 1A). The gut is short and bulbous; usually remnants of the yolk and oil globule are visible anteriorly in the region of the liver.

Relative body depth increases markedly during early larval stages and less so during later larval stages (Figures 1, 2). Body depth at the base of the pectoral fins averages 23% of the body length before notochord flexion, 33% during flexion, and 34% after flexion. In pelagic juveniles (Figure 3), relative body depth decreases slightly to about 30% in individuals 35 to 40 mm long. *S. paucispinis* is more slender throughout the larval and early juvenile stages; body depth averages 20% of the body length before notochord flexion, 24% during flexion, 31% following flexion, and 28% in pelagic juveniles.

Relative gut length increases gradually throughout the larval period. Accordingly, snout-anus length averages 42% of the body length before notochord flexion, 52% during flexion, 60% after flexion, 64% in pelagic juveniles. A similar gradual increase occurs in *S. paucispinis* (41, 44, 56, and 63% in the respective stages).

Relative head length increases slightly during the larval period; head length averages 28% of the body length before notochord flexion and 37% during and after flexion, but decreases during transformation and is 32% in the largest pelagic juveniles. Eye diameter averages 33% of the head length throughout the larval period and shows no trend of relative increase or decrease. Relative eye diameter decreases slightly to about 28% in transforming individuals, but increases to about 32% in the largest pelagic juveniles.

Upper jaw length is variable with respect to head length, probably because of the difficulty in obtaining uniform measurements from specimens with partially opened jaws. There is, however, a general trend of relative increase; jaw length averages 47% of head length before notochord flexion, 49% during flexion, and 52% in postflexion larvae. In large larvae and in pelagic juveniles the end of the maxillary is located beneath the middle of the orbit. With continued elongation of the maxillary in demer-

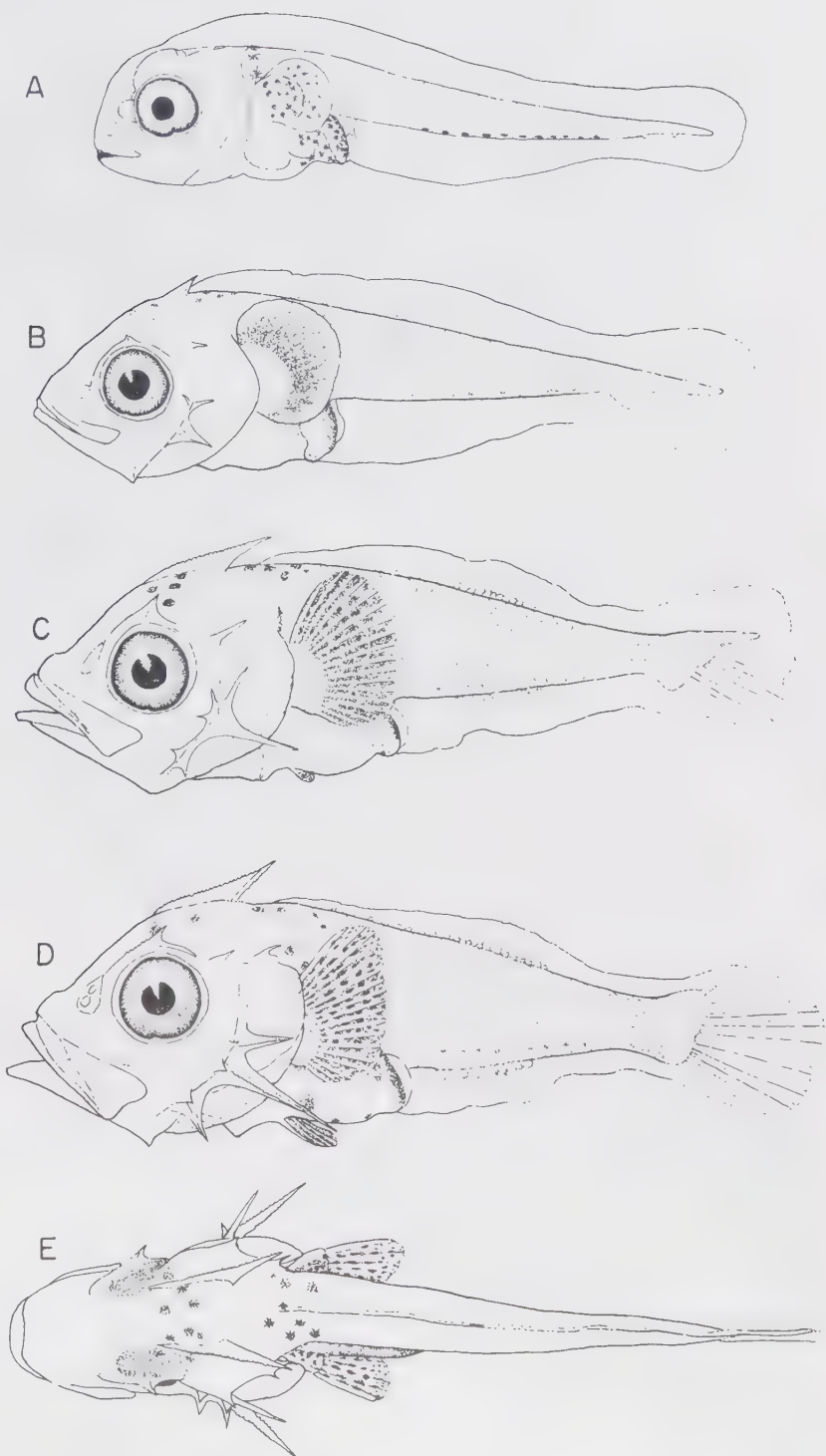


FIGURE 1.—Larvae of *Sebastes macdonaldi* from a pregnant female (A) and from California Cooperative Oceanic Fisheries Investigations (CalCOFI) plankton samples (B-E). A. 4.5 mm; B. 6.3 mm; C. 7.7 mm; D. 9.0 mm; E. dorsal view, 9.0 mm.

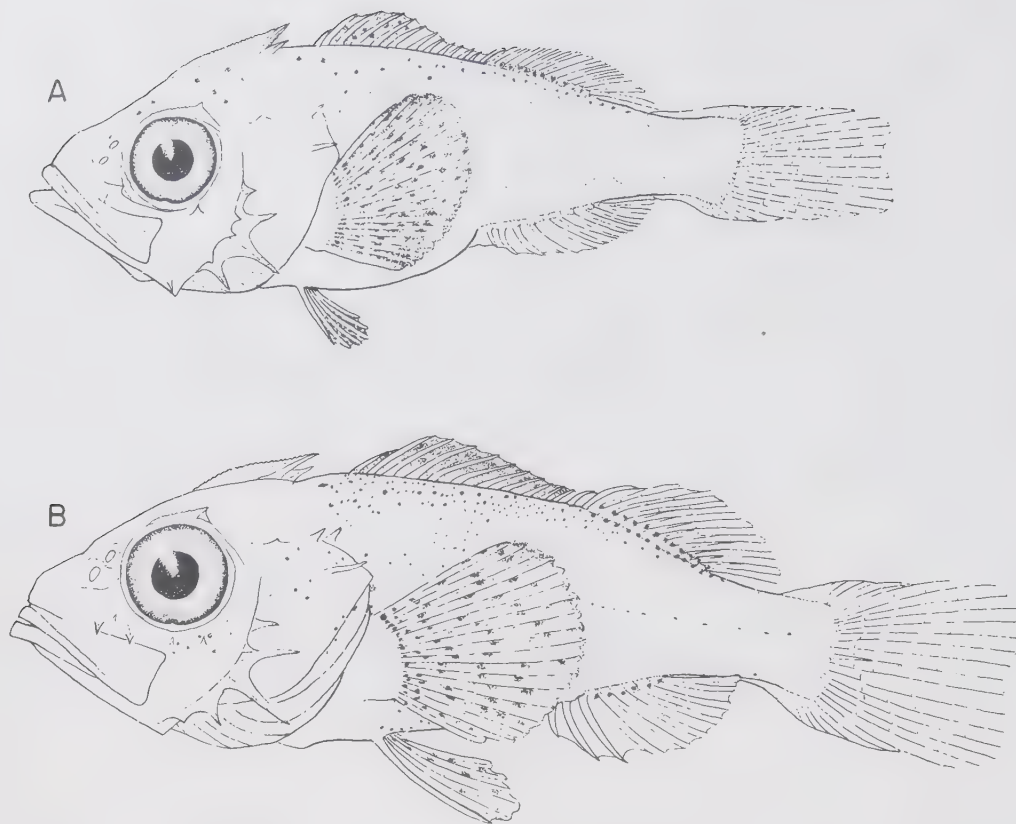


FIGURE 2.—Planktonic larvae of *Sebastes macdonaldi* from CalCOFI plankton samples. A. 11.2 mm; B. 15.9 mm.

sal juveniles (Figure 4) and in adults, its posterior end extends to below the posterior margin of the orbit. The relative length of the snout does not change markedly during the larval period; snout length averages 32% of the head length throughout the larval period. In pelagic juveniles snout length is reduced slightly to an average of 28% of the head length. Likewise, the width of the interorbital region changes little relative to head length in larvae; it averages about 46% of the head length. At the end of the larval period the interorbital distance becomes markedly narrower and averages 27% of the head length in pelagic juveniles. Similar changes in relative growth rate of the head, eyes, jaws, snout, and interorbital region occur in larvae and early juveniles of *S. paucispinis*.

FIN DEVELOPMENT

The pectoral fins begin to form during embryogenesis and, at parturition, the muscular base of each fin is distinct from the fan-shaped future rayed portion. The rayed portion enlarges considerably during early planktonic life and becomes covered solidly with melanophores (Figure 1B). The rays begin to ossify in larvae as small as 6.3 mm (Table 2); ossification begins with the most dorsal rays and then proceeds ventrad sequentially. Larvae 19.2 mm and larger have the full complement of 19 stained pectoral rays. The pectoral fins elongate slowly and gradually and have a short stubby appearance during most of the larval period. The length of the rayed portion of the fin averages 8% of

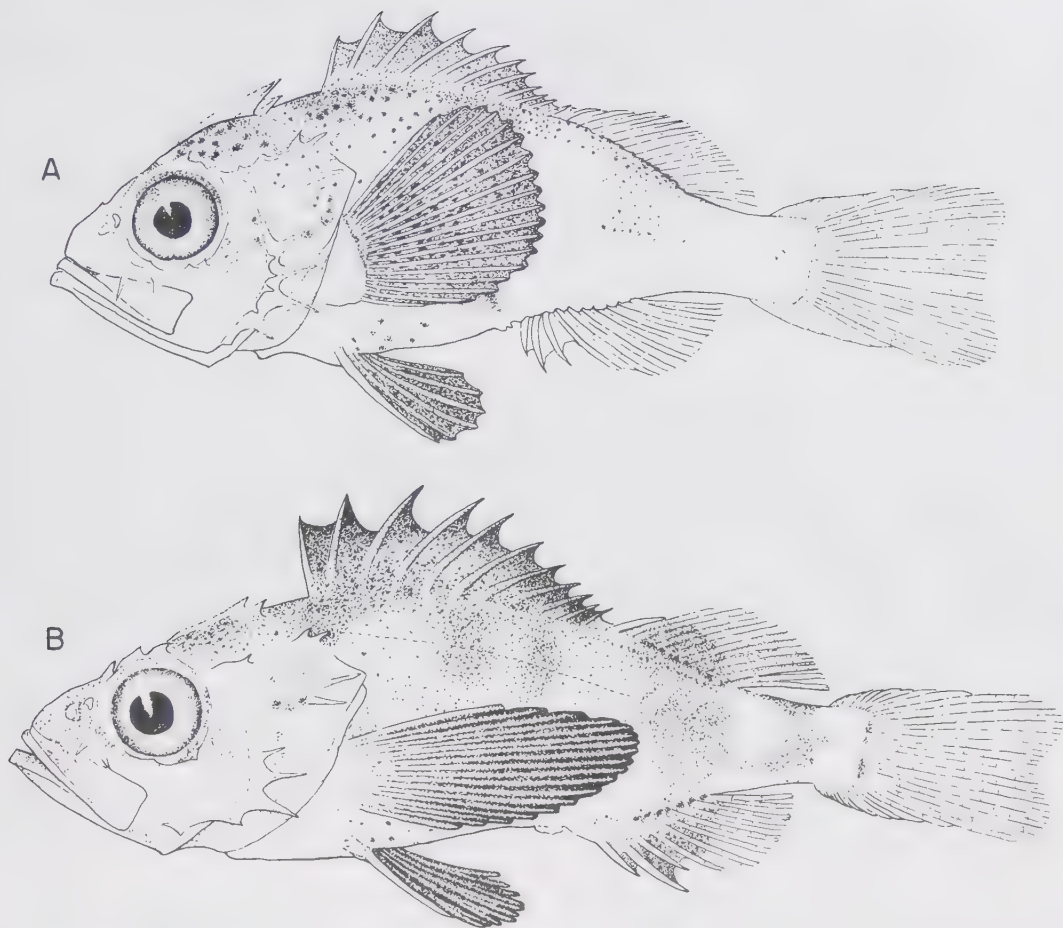


FIGURE 3.—Pelagic juveniles of *Sebastes macdonaldi*. A. A 15.4-mm transforming specimen (SIO 65-201, mid-water trawl) which is just beginning to develop its juvenile melanophore pattern. Note that it is further advanced than the 15.9-specimen in Figure 2. B. A 29.2-mm specimen dipnetted on surface at night (SIO 69-232).

the body length in the stages before notochord flexion, 13% during flexion, and 19% in the stages following flexion. The fin elongates markedly in pelagic juveniles in which its average length is 31% of the body length (Figures 3B, 4A). This sequence of gradual elongation of the pectoral fins throughout the larval and early juvenile period contrasts with that observed in *S. paucispinis* (Moser, 1967). In that species, the maximum length of the pectoral fins, 40% of the body length, is achieved in 13-mm larvae and, thereafter, the pectoral fin length decreases

relative to body length; pectoral fin length is 25% of the body length in newly transformed juveniles of *S. paucispinis*. In both species, the heavily pigmented pectoral fins are the most striking features of larvae and early juveniles.

The pelvic-fin buds appear early, in larvae as small as 6.3 mm, and become covered with melanophores. The rays begin to differentiate in 7-mm larvae. Ossification of the spines is visible initially in a 7.7-mm specimen in the stained series (Table 2). Ossification of the rays proceeds sequentially posteriad from the spines; the



FIGURE 4.—Juveniles of *Sebastes macdonaldi*. A. A 40.2-mm pelagic juvenile (LACM 8821-9) collected by mid-water trawl in the Gulf of California. B. A 62.1-mm demersal juvenile (SIO 65-227) collected by otter trawl near Point Tosco, Baja California.

full complement of five ossified rays is present in each fin in a 9.4-mm stained specimen. Like the pectoral fins, the densely pigmented pelvics elongate gradually throughout the larval period. Pelvic fin length increases from 4% of the body length at the initiation of notochord flexion to 10% at its completion. Following flexion, it increases gradually to a maximum of 18 to 21% of the body length in larvae 15.0 to 16.0 mm long. In pelagic juveniles pelvic fin length is 21 to 22% of the body length.

The caudal-fin anlage first appears in larvae about 5.0 mm long as a ventral thickening near the tip of the notochord. The cartilaginous hypural elements begin to differentiate when the larvae are about 6.0 mm (Figure 1B) and the maximum number of three superior and two inferior hypurals is present at about 8.0 mm. Ossification of these elements begins in larvae about

8.5 mm long and all hypurals, except the slender dorsal-most element of the superior series, are ossifying in a larva 9.2 mm long. Fusion accompanies further ossification in the superior series; in the largest larva the two larger superior elements have nearly fused into a single plate, while the slender uppermost element remains separate and has just started to ossify. In the inferior series the larger upper element has two centers of ossification which produce a solid calcified plate in the largest larva. The slender lowermost element is also well ossified but remains separate. Thus, larvae of 15-mm length have achieved the adult complement of two superior and two inferior hypurals. The principal caudal rays begin to ossify in 7-mm larvae (Table 2). Ossification proceeds dorsad in the superior series, above the midline of the fin, and ventrad in the inferior series; the adult complement of

8 + 7 principal rays is present in an 8.2-mm larva of the stained series. Also, the initial procurrent rays are ossifying in this specimen. Ossification of these rays proceeds anteriad in both superior and inferior series. The largest larva (15.9 mm) has 10 superior and 11 inferior ossified rays, but the full complement of 11 to 13 superior and 13 to 15 inferior rays is attained in pelagic juveniles.

The dorsal and anal fins are the last to appear. The bases of the fins appear in larvae 5.3 to 7.0 mm long (Figures 1B, C). Cartilaginous radial elements start to differentiate when the larvae are about 7.0 mm and the full complements of these elements are present in larvae 8.0 to 8.5 mm. Initial ossification of the spinous rays of these fins is visible in an 8.2-mm specimen in which the three anal spines and the anterior seven dorsal spines are stained. A larger, but apparently less advanced specimen, 8.7 mm long has only four stained dorsal spines and shows no stain on the anal spines. A 9.2-mm faintly stained larva has seven spinous and eight soft dorsal rays but shows no stain on the anal rays. The next larva in the stained series, 9.4 mm long, has the adult complement of III-7 anal and XIII-13 dorsal rays. The remaining larvae in the stained series, with the exception of one specimen, also have III-7 anal and XIII-13 dorsal rays.

PIGMENTATION

Newly hatched *S. macdonaldi* larvae have a melanophore pattern similar to that of *S. paucispinis*. The gut is covered with a mantle of melanophores that is solid on the dorsal surface and more sparsely distributed on the lateral and ventral surfaces (Figure 1A). A line of melanistic dashes on the ventral midline of the tail extends posteriad from the third or fourth post-anal myomere. In a sample of 60 newborn larvae of *S. macdonaldi* the number of melanophores in the ventral midline series ranged from 6 to 14 with a median of 8. Thus, this species has fewer ventral midline melanophores than any eastern Pacific species of *Sebastes* studied to date (see Morris, 1956; DeLacy et al., 1964; Moser, 1967). Head pigmentation in newborn larvae consists

of a series of melanophores that line the anterior region of the lower jaw and one to several melanophores that form a blotch on the nape. The pectoral fins also are pigmented; the inner surface of each fin base is covered solidly with melanophores while the lateral surface is pigmentless. The future rayed portion of the fin has sparsely distributed melanophores on both lateral and inner surfaces.

Melanophores are added throughout the larval period so that large larvae of *S. macdonaldi* are among the most heavily pigmented of all rockfish species (Figures 1, 2, 3). Much of the melanistic pigment is added in the head region. One or two melanophores appear over each optic lobe of the brain in 4- to 5-mm larvae. Similarly one or two melanophores appear above each side of the cerebellum in larvae of the same size. Melanophores are added continuously to the dorsal surface of the brain so that it is covered completely when the larvae reach 8.0 mm. Beginning in larvae about 7.0 mm long, isolated melanophores form anterior to the cleithra and eventually form a small patch that is covered by the opercle. When the larvae reach about 10.0 mm, considerably more pigment is added to the head. Patches of melanophores form around the external nares and along the anterior rim of the upper jaw; gradually the entire dorsal region of the snout becomes covered. Also, a conspicuous melanophore patch appears at the ventroposterior margin of the orbit and on the dorsal surface of the opercle.

Pigmentation on the gut, particularly on the dorsal and lateral surfaces, becomes more extensive during larval development. Beginning in larvae of about 5.0-mm length, melanophores are added in the region dorsal to the pectoral fin base and eventually a continuous band of melanophores extends from the gut to the enlarging melanistic blotch at the nape.

The number of melanophores in the series at the ventral midline of the tail appears to diminish as development proceeds; this may be an apparent reduction since the melanophores become embedded in the developing hypaxial musculature and later become obscured by the developing anal fin. Typically, in larvae larger than 8.0 mm the three posterior melanophores

in the series are visible along the ventral margin of the caudal peduncle while more anterior melanophores of the series are barely visible above the developing anal fin.

The paired fins are strikingly pigmented. Melanophores are added continuously to the rayed portion of the pectoral fin but are scattered until the larvae are about 7.0 mm long (Figure 1C) when they become concentrated on the membranous portions of the fins between the developing rays and give the fins a striated appearance that remains throughout the larval period. The base of the pectoral fin remains heavily pigmented only on the medial surface. Melanophores begin to appear on the pelvic fins in larvae about 7.0 mm long and form a striated pattern like the pectorals when the larvae reach a length of about 8.5 mm.

The median fins develop pigmentation considerably later in the larval period. When larvae reach about 9.0-mm length (Figures 1D, E), the melanophore patch on the nape begins to expand posteriad along the dorsal midline to form an elongated patch at the base of the spinous dorsal fin. A separate elongated patch of melanophores develops at the base of the soft dorsal fin and the two become connected by a narrow bridge of melanophores when the larvae reach about 10.0 mm. Melanophores begin to form on the anterior portion of the spinous dorsal fin when the larvae are about 9.0 mm long. Gradually the pigmented area of the fin enlarges until the entire spinous dorsal is pigmented in larvae longer than 15.0 mm (Figure 2B). Pigment on the soft dorsal fin is limited to a series of melanophores that covers the distal radial elements of the fin base. These melanophores begin to appear in 11-mm larvae and cover nearly all the radial elements when the larvae reach 15.0 mm (Figures 2A, B). A similar series of melanophores develops along the anal fin base when the larvae reach 12.0-mm length. One to several melanophores appear at the posterior margin of the hypural elements. In pelagic juveniles other melanophores are added here to form a vertical line (Figures 3B, 4A).

The beginnings of the juvenile pigment pattern appear in larvae 15.0 to 16.0 mm long when saddles of melanistic pigment start to develop

ventrad from the elongate patches that lie along the dorsal fin base (Figures 2B, 3A). The first of these extends ventroanteriorad from the origin of the dorsal fin to meet with the melanistic blotch on the opercle. A second saddle extends from the middle region of the spinous dorsal fin ventrad to overlies the lateral line, as does a third saddle which extends ventrad from the base of the soft dorsal fin.

These melanistic saddles become further developed in pelagic juveniles. In a 22.6-mm juvenile the pigment saddle at the soft dorsal fin extends almost to the base of the anal fin, and a fourth saddle is present at the caudal peduncle. In a 29.2-mm specimen (Figure 3B) the broad band at the soft dorsal is continuous and extends onto the rays of the dorsal and anal fins. The band at the caudal peduncle also extends to the ventral midline. Also, in this specimen, an additional saddle is present below the posterior end of the spinous dorsal fin, just posterior to the one located below the middle of the fin. In the largest pelagic juveniles (33-44 mm) the most anterior bar at the origin of the dorsal fin is obliterated as it becomes continuous with the solidly pigmented dorsal region of the head (Figure 4A). Melanistic pigment on the fins is augmented in pelagic juveniles. The entire spinous dorsal is dark and has a black margin whereas only the basal regions of the soft dorsal and anal fins are covered with melanophores. The caudal fin lacks melanophores. The pelvic fins remain pigmented as in late-stage larvae; however, a zone without melanophores develops on the basal third of each pectoral fin.

The melanistic pigment pattern of the smallest demersal juveniles (60 mm SL) remains essentially like that of pelagic juveniles (Figure 4). The smallest fresh specimens examined were 150 mm SL. In these the melanistic saddles and bands are separated by dusky areas above the horizontal septa. Below the septa, the background color is crimson, as is the lateral line and the head below the ventral margin of the orbit. The spinous dorsal fin is dusky with a black margin whereas the soft dorsal has a dusky base, a black central zone, and a pale margin. The caudal, anal, pelvic, and pectoral fins have crimson rays alternating with black between the rays.

In large adults the lateral melanistic patches and bands coalesce to form a solid black zone above the horizontal septa with a crimson zone below. At least the posterior half of the lateral line remains bordered by crimson. The spinous and soft dorsal fins become black. The caudal fin is black except for a vertical crimson zone at the base. The anal and ventral fins remain crimson with black between the rays. The pectoral fins become black except for a red zone at the proximal third of each fin.

SEQUENCE OF OSSIFICATION

The sequence of calcification of bones in larvae of *S. macdonaldi* is similar to that described for larvae of Myctophidae (Moser and Ahlstrom, 1970). As in myctophids, the maxillaries and cleithra are the first elements to ossify. In fact, the maxillaries, cleithra, and opercles are beginning to ossify in full-term intraovarian larvae. The sequence of ossification of other head, appendicular, and axial elements in a stained series of *S. macdonaldi* is shown in Table 3. For each element, the larval length at initial ossification and the larval length at which the element achieves its adult form are given. Selection of the point at which an element achieves its adult form, admittedly, is somewhat subjective since bone formation is a gradual process that continues throughout the life of the fish. In rockfish, as in most other teleosts, most of the skeletal elements become ossified during the larval period and assume a shape which, except for minor surface irregularities and processes, closely resembles that found in juveniles and adults. The branchial arches and cranial spines ossify gradually and generally have not achieved their adult form before the end of the larval period. For this reason these are listed in separate tables (Tables 4, 5), which give only the sequence of initial ossification.

Although the neurocranium is unossified in unborn larvae, the frontals, pterotics, and parasphenoid form soon after birth, in larvae 5.1 to 5.2 mm. These are followed by the parietals, exoccipital, basioccipital, and supraoccipital, and later the circumorbital bones and the more anterior neurocranial elements.

In the upper jaw the maxillaries begin to ossify before birth. These are followed by the main elements of the lower jaw, the dentaries and articulars, which begin to ossify at 5.1 to 5.2 mm. Other elements of the jaws, the premaxillaries and angulars, are beginning to ossify in a 6.3-mm stained larva. All elements of the mandibular arch achieve their adult form early in the larval period, between 7.0 and 8.5 mm. The elements of the palatine series are slower to ossify. The quadrates begin to ossify at about 6.3 mm and the others follow gradually; the last elements to initiate ossification, the palatines and metapterygoids, achieve their adult form in 12.0-mm and 15.9-mm larvae respectively.

The bones of the hyoid arch and opercular series initiate ossification gradually, beginning with the opercle in unborn larvae. The other bones of the opercular series have started to ossify before the larvae reach 6.3 mm, and all have achieved their adult form at 7.9 to 8.2 mm. Elements of the hyoid arch, particularly the ceratohyals and interhyals, are slower to initiate and complete ossification.

In the appendicular skeleton, the cleithra are the first bones to become ossified. They are heavily stained in unborn larvae and are the first skeletal elements to ossify. Following birth, the other bones of the pectoral girdle gradually initiate ossification. Among the last to appear are the four proximal radial elements, which ossify in a dorsal-to-ventral sequence. The coracoids and the single pair of extrascapulars initiate calcification at about 12.0 mm and are formed in the 15.9-mm specimen. The pelvic bones appear initially in a 9.2-mm stained specimen; through gradual ossification the pelvics become fused along their medial surfaces.

The paired neural arch elements are the first bones of the axial skeleton to ossify. At first only the most anterior pair is visible in a 7.0-mm larva, but gradually others are added in a posteriad sequence. When the larvae are about 8.0 mm long, the distal ends of each pair begin to fuse in the midline to complete the neural arch. This fusion and the resultant formation of a neural spine on each arch also occurs in an anterior to posterior sequence. The full complement of neural spines, including a shortened one

TABLE 3.—Sequence of ossification in larvae of *Sebastes macdonaldi*. The initial ossification of an element is indicated by "X" and the point of the arrow indicates the larval size at which the element achieves the general shape it will have in the juvenile and adult.

	4.5	4.7	5.1	5.2	5.6	5.8	6.3	6.7	6.8	7.0	7.1	7.2	7.7	7.9	8.2	8.5	8.7	9.2	9.4	9.7	10.0	10.3	11.3	12.0	15.0	15.9	
NEUROCRANIUM																											
Pterotic			X																								
Parasphenoid			X																								
Frontal			X																								
Parietal							X																				
Exoccipital							X																				
Basioccipital								X																			
Supraoccipital									X																		
Sphenotic										X																	
Lacrima											X																
Vomer												X															
Epiotic												X															
Prootic												X															
Jugal												X															
Antorbital													X														
Mesethmoid														X													
Dermosphenotic															X												
Infraorbital																X											
Nasal																		X									
MANDIBULAR ARCH																											
Maxillary	X																										
Dentary		X																									
Articular			X																								
Premaxillary							X																				
Angular							X																				
PALATINE SERIES																											
Quadrate							X																				
Mesopterygoid								X																			
Ectopterygoid									X																		
Palatine													X														
Metapterygoid														X													
HYOID ARCH and OPERCULAR SERIES																											
Opercular	X																										
Preopercular		X																									
Symplectic			X																								
Subopercular							X																				
Ceratohyal (anterior)							X																				
Hyomandibular							X																				
Interopercular								X																			
Urohyal									X																		
Ceratohyal (posterior)										X																	
Interhyal													X														
APPENDICULAR SKELETON																											
Cleithrum	X																										
Supracleithrum										X																	
Post-temporal										X																	
Post-cleithrum (ventral)											X																
Post-cleithrum (dorsal)												X															
Scapula															X												
Pelvic																		X									
Proximal radials (pectoral)																			X								
Coracoid																				X							
Extrascapular																					X						
AXIAL SKELETON																											
Neural arches & spines										X																	
Vertebral Centra											X																
Ural Centrum												X															
Haemal arches and spines														X													
Urochordal															X												
Proximal radials (dorsal fin)																		X									
Proximal radials (anal fin)																			X								
Interneural																					X						
Ribs																							X				

TABLE 4.—Sequence of initial ossification of branchial arch elements in larvae of *Sebastes macdonaldi*.

Element	Larval length at initial ossification (mm)
Pharyngobranchial teeth (3rd arch)	4.7
Ceratobranchial (1st arch)	6.3
Ceratobranchial (2nd arch)	6.3
Ceratobranchial (3rd arch)	6.3
Ceratobranchial (4th arch)	6.7
Ceratobranchial gill rakers (1st arch)	6.7
Ceratobranchial gill rakers (2nd arch)	7.2
Epibranchial (1st arch)	7.2
Epibranchial (2nd arch)	7.2
Ceratobranchial teeth (5th arch)	7.2
Ceratobranchial (5th arch)	7.7
Epibranchial (3rd arch)	7.7
Pharyngobranchial teeth (4th arch)	7.7
Ceratobranchial gill rakers (3rd arch)	7.7
Epibranchial gill rakers (1st arch)	8.2
Epibranchial (4th arch)	8.2
Hypobranchial (1st arch)	8.7
Epibranchial gill rakers (2nd arch)	8.7
Basibranchials	9.2
Hypobranchial (2nd arch)	9.2
Hypobranchial (3rd arch)	9.4

on the ultimate preterminal vertebra, is present in a 15.0-mm stained specimen.

The next elements of the axial skeleton to appear are the vertebral centra. The most anterior centra begin to ossify in larvae about 7.2 mm long. Ossification within each centrum begins at the bases of the neural arch and spreads medially to form a straplike bridge between the bases. A similar structure forms ventrally between the bases of the haemal arch and ultimately the two bridges are joined by lateral ossification, to produce a complete central ring. This process proceeds in a posteriad sequence until the full complement of 25 central rings is attained in larvae of about 10.0 mm. Ossification of the ural centrum begins in an 8.2-mm specimen with the formation of two tandem osseous plates on each lateral surface. These spread rapidly to cover the entire lateral and dorsal surface of the centrum. Ossification of two ventral unossified regions is completed at about 10.0 mm to coincide with the formation of the ultimate preterminal centrum.

Haemal arches begin to ossify at about 8.2-mm length in a manner similar to that of the neural arches. Closure of the haemal processes into arches and the formation of haemal spines proceeds posteriad sequentially; when completed at 10.0 mm, vertebrae 1 to 4 are without haemal

TABLE 5.—Sequence of initial ossification of head spines of larvae of *Sebastes macdonaldi*.

Spine	Element	Size of specimen at initial appearance (mm)
Pterotic	Pterotic	5.1
Preopercular, 3rd, posterior series	Preopercular	5.1
Preopercular, 4th, posterior series	Preopercular	5.2
Parietal	Parietal	6.3
Postocular	Frontal	6.3
Preopercular, 1st, anterior series	Preopercular	6.3
Preopercular, 2nd, anterior series	Preopercular	6.3
Preopercular, 3rd, anterior series	Preopercular	6.3
Preopercular, 2nd, posterior series	Preopercular	6.7
Supracleithral	Posttemporal	7.7
Suborbital, 1st, inferior series	Lacrimal	8.2
Suborbital, 1st, superior series	Lacrimal	8.2
Preopercular, 1st, posterior series	Preopercular	8.2
Nuchal	Parietal	8.2
Opercular, 1st	Opercle	8.2
Opercular, 2nd	Opercle	8.2
Preopercular, 5th, posterior series	Preopercular	9.4
Suborbital, 3rd, superior series	Jugal	9.4
Cleithral	Supracleithrum	12.0
Nasal	Nasal	15.0
Suborbital, 2nd, inferior series	Lacrimal	15.0
Suborbital, 2nd, superior series	Infraorbital	15.0
Preocular	Antorbital	22.6
Supraocular	Frontal	22.6
Tympanic	Frontal	22.6

processes, 5 to 9 have unfused haemal processes, 10 and 11 have haemal arches without spines, and 12 to 25 have arches and spines.

All of the remaining major axial elements begin to ossify in larvae 10.0 mm or longer. The uroneurals appear as a pair of slender elements above the terminal centrum in a 10.0-mm specimen; they remain paired and sliverlike throughout the larval period. The proximal radial elements of the dorsal fin also begin to ossify at 10.0 mm and those of the anal fin at 12.0 mm, both in a posteriad direction; neither series is completed by 15.9 mm. A single interneural appears slightly above and in advance of the first neural spine in a 15.0-mm larva. Also, in this specimen the most anterior few ribs have just begun to ossify.

Several generalizations can be made from the information listed in Table 3. It is obvious that the various skeletal elements begin to ossify over a wide range of larval sizes and that the elements vary greatly in the time required for each to attain its adult form. For example, in the neurocranium, the jugal (third circumorbital) is formed over a span of nearly 7.0-mm length (8.2-15.0 mm) while the vomer begins to ossify

and achieves its adult shape over a span of about 1.0 mm (7.7-8.5 mm). Similar variation is found in the mandibular, palatine, and hyoid arches and in the axial and appendicular skeletons. Another less obvious generalization from Table 3 is that functionally related contiguous elements tend to achieve their adult form at about the same larval stage, regardless of when they underwent initial ossification. For example, the first six bones listed in the table are the major elements of the roof, sides, and floor of the brain case. Although they undergo initial ossification in a gradual sequence, all achieve their adult form in larvae 7.9 to 9.2 mm long. The bones of the opercular series (opercular, preopercular, subopercular, interopercular) begin to ossify in successive stages, but all achieve adult form at about the same stage. The pectoral girdle provides two excellent examples of this tendency in the cleithrum-supracleithrum-posttemporal series and the scapula-proximal radial-coracoid series. Finally, there is no correlation between sequence of ossification and the origin (endochondral or dermal) of a bony element. Thus, of the first six elements of the neurocranium mentioned above, half are endochondral and half are dermal in origin. Here, the early appearance of these elements appears to be related to function and not to the kind of bone formed.

Analysis of the sequence of ossification of branchial elements is difficult since ossification is so gradual that one cannot choose a larval stage at which a given element achieves its basic adult form. Accordingly, only the larval size at which an element begins to ossify is listed in Table 4. As in other teleosts examined by me, the first bony structures to ossify in the larvae are the pharyngobranchial teeth. In *S. macdonaldi*, the tooth patches of the third pair of pharyngobranchial elements appear in the smallest planktonic larvae and enlarge throughout the larval period. In larvae of the Myctophidae it is the tooth patches of the fourth pharyngobranchials which ossify first (Moser and Ahlstrom, 1970). Aside from this, the sequence of ossification is similar in *Sebastes* and Myctophidae. The ceratobranchials are the first elements of the arches to ossify. These are followed by the epibranchials and hypobranchials,

generally in an anterior to posterior sequence, beginning with those of the first arch. The first gill rakers to form are those on the first pairs of ceratobranchials and epibranchials and, gradually, they appear on more posterior arches. Within each arch, ossification proceeds outward from the angle of the arch. The full complement of rakers on the first arch is not achieved during the larval period.

Head spines present a special problem since some of the spines formed during the larval period are not found in adults. The terminology of Phillips (1957) is used in the discussion that follows. The first spines to form on the neurocranium are on the pterotic bones (Table 5). Interestingly, these spines begin to ossify before the bones themselves, and ossification of the bones spreads outward from the base of each spine. The spines are at first acute, but broaden during the larval period to produce a pterotic shelf in the largest larvae. The spine and shelf become reduced in pelagic juveniles and are absent in demersal juveniles and in adults. The two other pairs of spines which develop early in the larval period are the parietals and postoculars. The paired parietal spines develop as the terminal points of a pair of serrated parietal ridges and attain their maximum relative length (20-23% of the head length) in larvae 8.0 to 10.0 mm long. The ridges and their spines become reduced during later larval stages but remain in juveniles and adults. The postoculars develop from lateral shelves of the frontal bones that project over the eyes. Initially the spines are positioned directly above the eyes but gradually shift posteriad to their adult position. Preocular, supraocular, and tympanic spines do not form during the larval period; they are beginning to form in a pelagic juvenile 22.6 mm long and are well formed in the largest pelagic juveniles.

Other prominent cranial spines which develop later in the larval period are the suborbitals, nuchals, and nasals (Table 5). The suborbital spines form in two series: one series of ventrally directed spines develops on the ventral margin of each lacrimal (first circumorbital) bone and another series of laterally directed spines forms directly below the orbit. This lat-

ter series, composed of a single spine on each lacrimal, infraorbital, and jugal element, forms a shelf in late-stage larvae and in juveniles, but usually only the lacrimal spine remains in adults. The inferior series persists in adults and typically contains 3 to 5 spines. A nuchal spine forms directly posterior to each parietal spine in larvae about 8.0 mm long and persists in juveniles and adults. Nasal spines are late to form (15.0 mm) but also persist in adults.

Two spines appear on each preopercle in larvae 5.1 to 5.2 mm long. These are the third and fourth members of a series of five preopercular spines that forms throughout the larval period (Table 5). The third preopercular spines develop three longitudinal serrated ridges and elongate rapidly to become the longest larval spines. They reach a maximum length of 35% of the head length in larvae about 9.0 mm long and then decline in relative length. The five preopercular spines remain in juveniles and adults, but the short spines which develop immediately anterior to the second, third, and fourth preoperculars (Table 5) become obsolescent after the larval period. A pair of spines forms at the posterior margin of each opercle and persists in juveniles and adults.

The supracleithral and cleithral spines develop during the larval period; the supracleithral spines form on the posttemporal elements in larvae about 7.7 mm long and the cleithral spines form on the supercleithra at about 12.0 mm. Both pairs persist into the adult stage.

DISTRIBUTION

S. macdonaldi has the most southerly distribution of any species of *Sebastes* in the eastern north Pacific. Chen (1971) lists its southern range record as Morgan Bank off Baja California (lat 23°24.0'N, long 111°11.5'W) and reports on the capture of a single adult specimen (LACM 8837-4) from Santa Inez Bay in the Gulf of California (lat 26°59.1'N, long 111°48.9'W). A collection of six pelagic juveniles (32.7-44.4 mm SL; LACM 8821-9) by midwater trawl from the Ballenas Channel in the Gulf of California (lat 28°56.5'N, long 113°10.5'W) is reported herein. Although the localities at Morgan Bank and

Santa Inez Bay are separated by a distance of approximately 1,000 km, it is likely that future collections in this region will substantiate Chen's (1971) suggestion that the outer coast and Gulf of California populations are continuous.

The southerly distribution of *S. macdonaldi* is shown by the distribution of the larvae (Table 6, Figure 5). For the 4 years examined, larvae were taken as far north as CalCOFI line 90 and as far south as line 137. Line 90, running southwesterly from Dana Point, Calif., probably delimits the northern extent of reproduction for this species, although an adult has been taken as far north as Pt. Sur, Calif. (Phillips, 1961). Total numbers of larvae and frequency of occurrence of larvae increase to the south of line 90.



FIGURE 5.—Stations at which larvae of *Sebastes macdonaldi* were collected during 4 years (1953, 1960, 1965, and 1966) of CalCOFI plankton surveys. Solid circles indicate stations where number of *Sebastes macdonaldi* larvae exceeded mean number (4.8) for all positive stations. Area of frequent occupancy is outlined (see Ahlstrom, 1961, for complete grid).

TABLE 6.—Total numbers of *Sebastes macdonaldi* larvae taken on 14 CalCOFI lines for 4 years (1953, 1960, 1965, and 1966) and abundance of larvae of this species compared with the total numbers of *Sebastes* larvae taken in hauls containing *S. macdonaldi*.

CalCOFI line	Latitude ¹	Total number stations occupied	Total stations containing <i>S. macdonaldi</i>	Percentage of positive stations to total stations	Number of <i>S. macdonaldi</i> larvae	Total number of <i>Sebastes</i> larvae in hauls containing <i>S. macdonaldi</i>	Percentage <i>S. macdonaldi</i> larvae of total <i>Sebastes</i> larvae in hauls positive for <i>S. macdonaldi</i>
90	33°28.5'	383	1	0.26	1	31	3
93	32°56.0'	380	1	0.26	1	4	25
97	32°17.5'	325	1	0.31	1	28	4
103	31°07.0'	283	4	1.41	9	226	4
107	30°27.9'	273	8	2.93	12	226	5
110	29°52.0'	306	9	2.94	17	202	8
113	29°24.2'	283	19	6.71	47	285	16
117	28°58.0'	315	47	14.92	289	968	30
120	28°25.0'	365	33	9.04	110	332	33
123	27°26.2'	198	28	14.14	151	613	25
127	26°57.5'	202	33	16.34	143	252	57
130	26°33.5'	243	22	9.05	37	100	37
133	26°08.5'	209	23	11.00	207	224	92
137	25°36.1'	214	15	7.01	39	45	87

¹ Latitude of most shoreward station of each CalCOFI line.

They attain their largest numbers from line 117 to line 127 (Cedros Island to San Hipolito Point) and then decrease to line 137. In contrast, for those hauls containing *S. macdonaldi*, the ratio of this species to the total number of *Sebastes* larvae in these hauls increases continuously southward. *Sebastes* larvae were not taken on lines south of 137, probably because of the infrequent occupancy of these lines. Reproduction of *S. macdonaldi* occurs as far south as Morgan Bank (between lines 147 and 150), since one of the two specimens collected there was a term female with viable larvae.

The seasonal abundance and size of *S. macdonaldi* larvae at all CalCOFI stations during 1953 and 1960 are shown in Table 7. Larvae began to appear in January, increased in numbers in February, and reached a peak in March. Abundance declined progressively from April to June. The mean length of the larvae increased slightly during the 6-month period and the largest larvae were collected from March to June.

The larval stage is ended at about 16 mm; indeed, a 15.4-mm specimen is already beginning to develop the juvenile melanophore pattern and the juvenile arrangement of cranial spines. The pelagic juveniles are rare in plankton collections, probably because of their ability to avoid plankton nets. Also, they may occur deeper than 140 m, the usual maximum depth of CalCOFI plankton tows. Nevertheless, a number of pelagic juveniles, 22.6 to 44.4 mm long, were captured by plankton net, midwater trawl, and dip net. These are listed in Table 1 and discussed in the previous section of the paper. The smallest juvenile collected by bottom trawl was 59.3 mm. This suggests that the transition from pelagic to demersal habitat occurs in the size range of about 45 to 60 mm. Demersal juveniles 60 to 100 mm are captured typically at a depth range of 80 to 100 m. With further growth they appear to seek deeper habitats as there is a trend for larger fish to be collected from greater depths. The largest specimen examined (532

TABLE 7.—Numbers (A), mean length in mm (B), and size range in mm (C) of *Sebastes macdonaldi* larvae taken during 2 years of the California Cooperative Oceanic Fisheries Investigations (CalCOFI).

Year	CalCOFI lines	JANUARY			FEBRUARY			MARCH			APRIL			MAY			JUNE		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1953	97-107	2	4.2	4.2	4	4.2	4.2-4.3	0	0	0	1	4.8	4.8	0	0	0	0	0	0
	110-120	5	4.3	3.8-5.3	19	4.5	3.5-7.1	138	5.0	3.3- 9.5	26	6.2	3.7-10.0	4	4.8	3.8-6.2	0	0	0
	123-137	13	4.4	3.3-3.5	20	4.6	3.9-8.7	143	4.8	3.3-11.2	34	5.3	3.8- 8.8	5	5.4	3.3-9.6	0	0	0
1960	97-107	0	0	0	6	5.1	4.3-6.5	6	5.6	4.7- 8.2	2	4.9	4.9	0	0	0	0	0	0
	110-120	0	0	0	12	4.7	4.4-5.2	81	5.2	3.8- 8.8	25	4.8	4.0- 6.2	4	5.3	4.5-7.3	5	4.3	3.7-5.8
	123-137	1	4.2	4.2	14	4.9	4.0-5.8	184	4.7	3.4-10.8	76	5.2	3.2-10.3	17	5.1	4.1-9.6	1	6.0	6.0

mm SL, SIO 65-126) was taken by hook and line at 256 m.

ACKNOWLEDGMENTS

I am indebted to a number of people for their help during this study and in the preparation of this manuscript. George Mattson of the National Marine Fisheries Service (NMFS, La Jolla) provided the drawings and photographs of the larvae and juveniles. James Thrailkill (NMFS, La Jolla) drafted the distribution chart. Dr. Paul Smith (NMFS, La Jolla) made helpful suggestions during preparation of the distribution section of the paper, and Mrs. Esther Barker helped prepare this data. Miss Amelia Gomes and Mrs. Elaine Sandknop (NMFS, La Jolla) cleared and stained the larval series.

Specimens were kindly provided by Dr. Richard Rosenblatt (Scripps Institution of Oceanography), Dr. Lo-chai Chen (San Diego State College), Dr. Robert Lavenberg (Los Angeles County Museum of Natural History), and John Bleck (University of California, Los Angeles). John Fitch (California Department of Fish and Game) furnished information on the geographic range of juveniles and adults. Dr. Jørgen Nielsen (Zoological Museum, University of Copenhagen) read the manuscript and offered helpful suggestions. Special thanks are due Dr. Elbert Ahlstrom (Senior Scientist, NMFS, La Jolla) for his helpful discussions and encouragement throughout this study.

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DEVELOPMENT OF THE LANTERNFISH, *SCOPELOPSIS MULTIPUNCTATUS* BRAUER 1906, WITH A DISCUSSION OF ITS PHYLOGENETIC POSITION IN THE FAMILY MYCTOPHIDAE AND ITS ROLE IN A PROPOSED MECHANISM FOR THE EVOLUTION OF PHOTOPHORE PATTERNS IN LANTERNFISHES

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ABSTRACT

The larval and transformation stages of the unusual myctophid, *Scopelopsis multipunctatus* Brauer, are described. A character that the larvae of *Scopelopsis* share with a number of other genera in the Lampanyctinae is the sequential development of three or more pairs of early forming photophores. The sequence of development of early forming photophores is shown to be an especially useful character in revealing phylogenetic affinities when used in conjunction with other larval characters, such as body shape and pigment pattern. From our study of the development of *Scopelopsis*, a possible mechanism for the evolution of photophore patterns within the family Myctophidae is presented.

Brauer (1906), in his elegant report on the fishes collected during the German Deep-Sea Expedition of 1898-99, described for the first time a remarkable lanternfish, for which he established the genus *Scopelopsis*. His single specimen, a newly transformed juvenile, was unique in having the head and body studded with minute light organs, all of approximately the same size. All other lanternfish known to him were characterized by a specific pattern of photophores on the head and on the ventral and lateral regions of the body. These he grouped into the single genus *Myctophum*, under which he recognized four subgenera: *Myctophum*, *Diaphus*, *Lampanyctus*, and *Lampadena*. These two genera, along with *Neoscopelus*, a genus with an undifferentiated pattern of ventral photophores, and five other genera were included in the family Scopelidae.

Regan (1911) modified drastically this taxonomic arrangement by distributing Brauer's eight genera of scopelids into a scheme of three suborders. He placed the family Myctophidae within one of these suborders and included with-

in it seven genera: *Scopelopsis*, *Neoscopelus*, *Scopelengys* (a genus related to *Neoscopelus* but lacking photophores), and the four subgenera of Brauer raised to generic rank. Parr (1928) further differentiated the family Myctophidae to include three subfamilies: Scopelengini for *Scopelengys*, Neoscopelini for *Neoscopelus*, and *Scopelopsis*, and Myctophini for *Myctophum*, *Lampanyctus*, *Diaphus*, and *Lampadena*.

Tåning (1932) noted that in a number of well-preserved specimens of *Scopelopsis*, certain photophores were larger and better developed than others, and that the scales covering these organs were equipped with the same lens-like modification typical of other members of Parr's Myctophini. He observed further that these larger photophores formed a pattern that corresponded with the kinds of photophore patterns found in the Myctophini and concluded, accordingly, that *Scopelopsis* belonged with *Myctophum*, *Lampanyctus*, and relatives in the subfamily Myctophini.

Fraser-Brunner (1949) reduced the number of subfamilies in the Myctophidae to two: The Neoscopelinae, to include *Neoscopelus*, *Scopelengys*, and *Solivomer*, and the Myctophinae, to in-

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clude *Scopelopsis* and 20 other genera. He provided the first substantial description of the photophore pattern of *Scopelopsis* and, in his illustration, differentiated the more conspicuous "primary" photophores from the minute "secondary" organs. Further, he recognized two major evolutionary lineages among these 21 genera and placed *Scopelopsis* among the group which included *Lampanyctus* and its relatives.

Authors since Smith (1949) have afforded full family status to the neoscopelines, separating the three genera from the Myctophidae. Recently, Paxton (1968) reviewed the osteology of the Myctophidae and constructed a higher classification to reflect generic relationships within the family. His views have been stimulative and complementary to our studies of larval myctophids (Moser and Ahlstrom, 1970). Our recent discovery of the larvae of *Scopelopsis* has served to crystallize our views of relationships within that part of the family which contains *Lampanyctus* and its allies. These ideas, based chiefly on larval morphology and sequence of photophore development, are set forth herein, following the description of *Scopelopsis* larvae.

MATERIALS AND METHODS

The developmental series of *Scopelopsis* used in this study was obtained chiefly from the R.R.S. *Discovery* plankton collections, housed at the British Museum (Natural History). A total of 29 specimens was taken off South Africa at stations 412, 413, 416, 418, 419, and 438 in August-September 1930. An additional five larvae were found on station 2352, occupied off South Africa in July 1938. A single transforming specimen came from station 2280 of the U.S. Antarctic Project ship *Eltanin*. Although adult specimens of *Scopelopsis* were obtained on EASTROPAC surveys, larvae were not taken.

A series of 25 specimens, from smallest larva to juveniles, was measured according to the method described in Moser and Ahlstrom (1970), to produce the table of morphometrics essential for description of the changes in body proportions. These specimens also were used for describing the development of the melanophore

pattern and of photophores. A second series of 11 larvae was cleared with KOH and stained with Alizarin Red-S; a table of meristics was constructed from counts made on these specimens.

For purposes of discussion we have included information and illustrations of nine genera related to *Scopelopsis*. These specimens and data, accumulated over an extended period of time, have come largely from the plankton collections of the California Cooperative Oceanic Fisheries Investigations, the NORPAC Expedition, the EASTROPAC Expedition, and the Danish Oceanographic Expedition, in addition to the two sources mentioned above. Where specimens from these and other sources are illustrated, appropriate station data are included in the caption accompanying the figure.

DESCRIPTION OF DEVELOPMENT OF *SCOPELOPSIS MULTIPUNCTATUS*

(Figures 1-3)

LITERATURE

Regan (1916) described the species *Lampanyctus longipinnis* from a 15-mm larval specimen. Judging from the fin counts given in the description and from the somewhat illegible drawing, the specimen was a larva of *Scopelopsis multipunctatus*.

MORPHOLOGY

Larvae of *Scopelopsis* are moderately slender. Body depth at the pectoral fin base is 18-19% of the body length in larvae undergoing notochord flexion and is 20-24% (mean of 22%) in later larval stages and transforming specimens (Table 1). The gut is of moderate length in specimens undergoing notochord flexion; snout-anus length is 44-45% of body length. The gut is conical in these specimens and gradually arches posteriad to the short terminal section. Snout-anus distance increases slightly in later larval and transforming specimens, which have a snout-anus length of 50-54% (mean of 52%) of body length. In these, the gut is covered by trunk musculature.

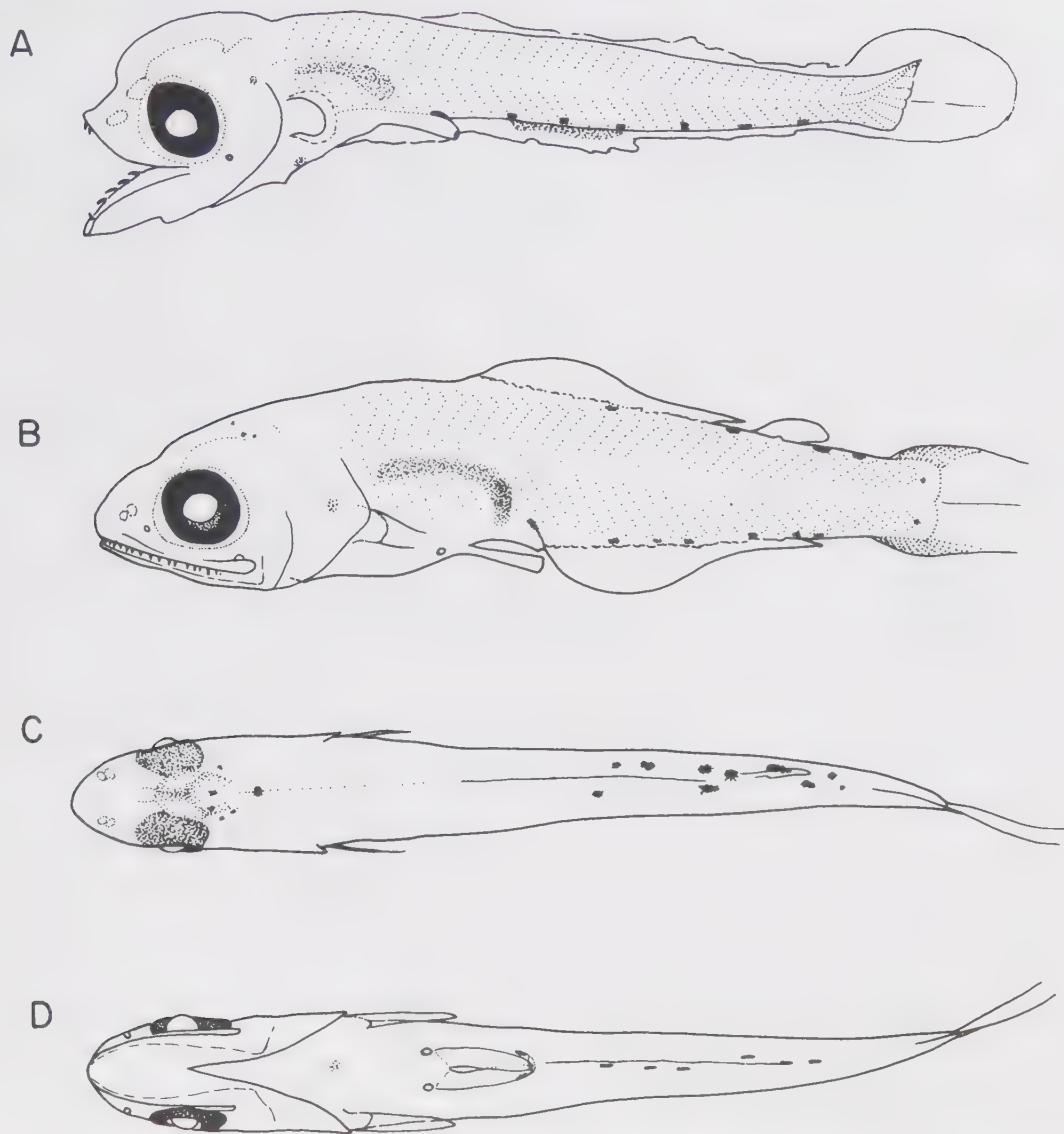


FIGURE 1.—Developmental stages of *Scopelopsis multipunctatus* Brauer.—A, 5.4-mm larva, R.R.S. *Discovery* Station 2352; B, 11.3-mm larva, R.R.S. *Discovery* Station 2352; C, 11.3-mm larva, dorsal view; D, 11.3-mm larva, ventral view.

The head is moderately large, its length being 24-28% (mean of 27%) of the body length for the larval series. The dorsal profile of the snout is concave in our smallest specimen (5.4 mm), but is straight in a 6.2-mm larva, and becomes distinctively bulbous in later larvae and in transforming specimens. The eyes are large in

Scopelopsis larvae, but undergo a slight diminution, relative to head size, with progressive larval development. Eye length measured vertically is 38% of the head length in the smallest larva, but decreases to 35% in a 6.2-mm larva. This dimension averages 30% of the head length in larvae which have completed notochord flexion,

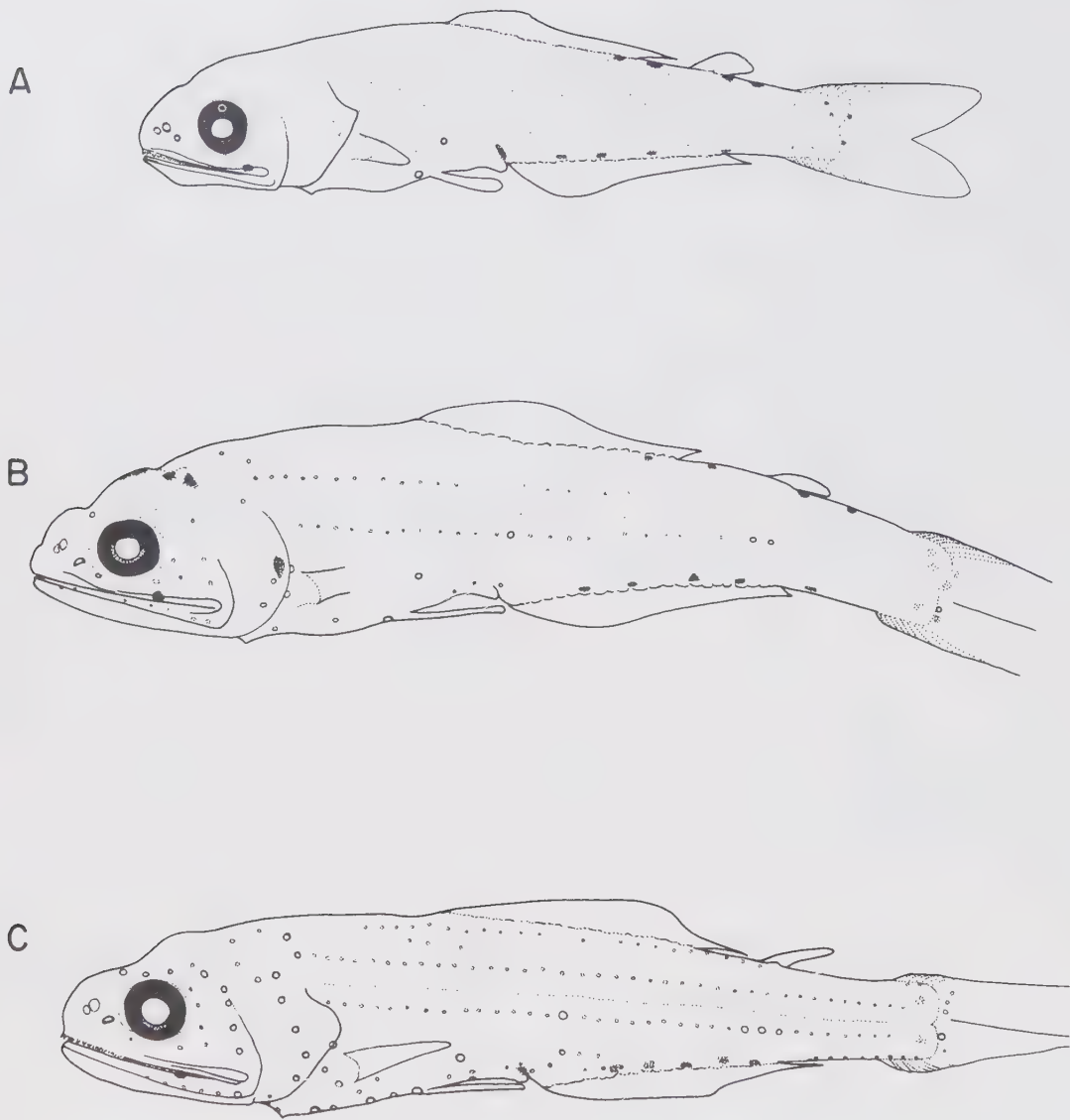


FIGURE 2.—Developmental stages of *Scopelopsis multipunctatus* Brauer.—A, 13.4-mm larva, R.R.S. *Discovery* Station 412; B, 17.6-mm transformation stage, R.R.S. *Discovery* Station 2280; C, 16.7-mm transformation stage, R.R.S. *Discovery* Station, 419.

but this is reduced to an average of 25% in transforming specimens and to 22% in a newly transformed juvenile. The eyes are round or nearly so in *Scopelopsis*; eye width, measured horizontally, averages 92% of eye length for the larval series. In the 17.4-mm juvenile, the horizontal measurement is slightly greater than the

vertical. Choroid tissue is absent from the ventral surface of the eye. The initial lateral teeth of the lower jaw are characteristically curved anteriorly. Later, the more typical dentary teeth form anterior to the curved teeth; the latter occupy the posterior half of each dentary in larger larvae.

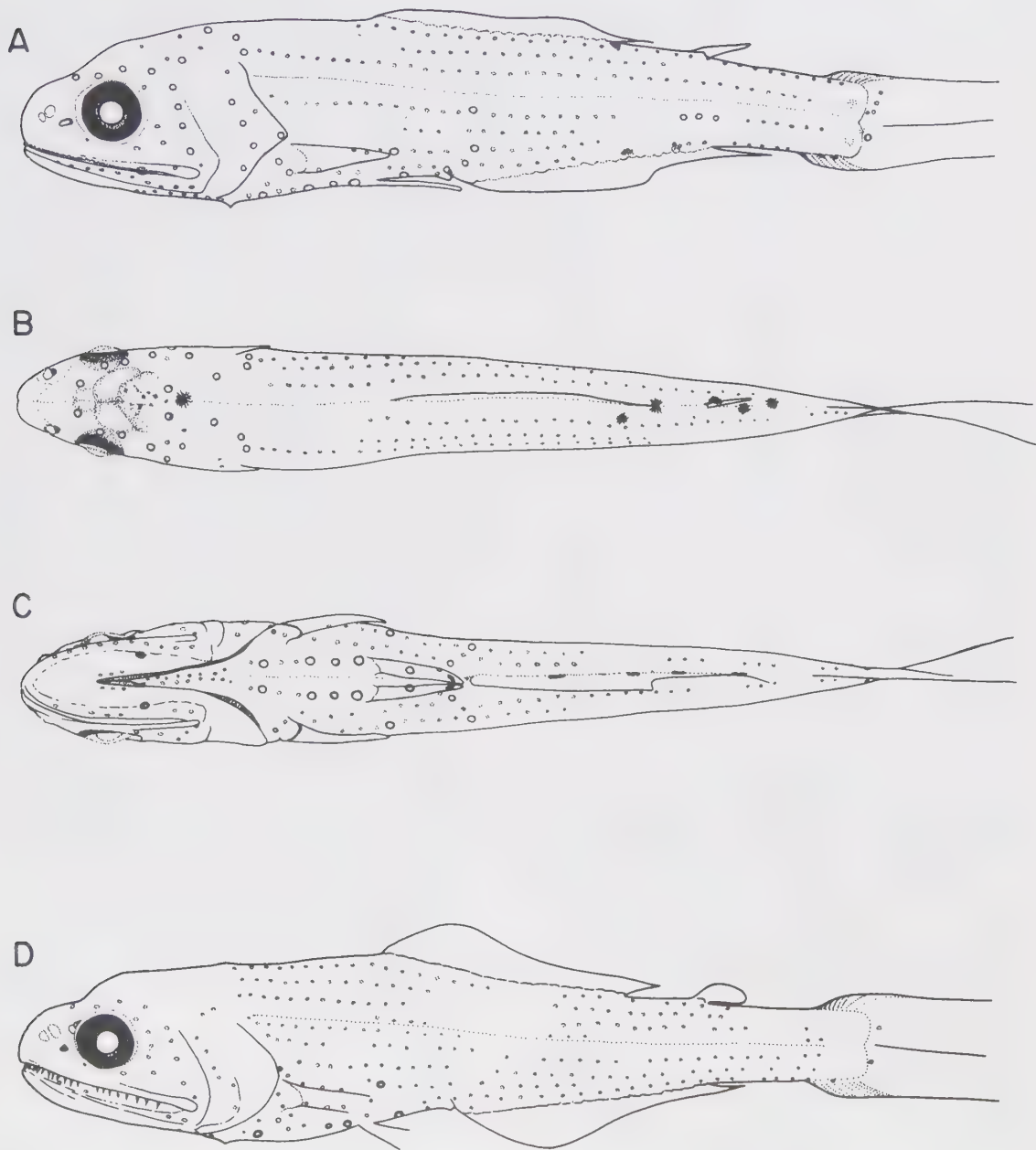


FIGURE 3.—Developmental stages of *Sceloporus multipunctatus* Brauer.—A, 17.5-mm transformation stage, R.R.S. Discovery Station 419; B, 17.5-mm transformation stage, dorsal view; C, 17.5-mm transformation stage, ventral view; D, 17.4-mm juvenile, R.R.S. Discovery Station 412.

TABLE 1.—Measurements (mm) of larvae of *Scopelopsis multipunctatus*. (Specimens below dashed line have completed notochord flexion.)

Body length	Snout to anus	Head length	Head width	Inter-orbital width	Body depth at base of pectoral fin	Eye length	Eye width	Snout to origin of anal fin	Snout to origin of dorsal fin	Snout to origin of pelvic fin
5.4	2.4	1.3	0.76	0.46	1.0	0.50	0.43	2.8	--	--
6.2	2.8	1.7	0.87	0.58	1.1	0.59	0.52	3.1	2.8	2.4
10.8	5.4	2.8	1.4	1.2	2.2	0.87	0.81	5.4	4.6	4.1
11.3	5.8	3.2	1.5	1.3	2.5	1.0	0.95	5.8	5.0	4.6
12.2	6.4	3.2	1.6	1.3	2.7	1.0	0.90	6.4	5.2	4.8
12.3	6.3	3.2	1.6	1.3	2.6	0.94	0.86	6.3	5.2	4.8
12.4	6.5	3.3	1.7	1.4	2.6	1.0	1.0	6.5	5.4	5.0
12.8	7.1	3.3	1.8	1.4	3.0	1.1	1.0	7.1	5.6	5.4
13.0	6.8	3.4	1.7	1.4	2.8	1.0	0.95	6.8	5.7	5.2
13.1	7.1	3.4	1.8	1.5	3.1	1.0	0.91	7.1	5.9	5.3
13.2	6.7	3.2	1.8	1.5	2.8	0.97	0.83	6.8	5.5	5.2
13.4	7.0	3.6	2.1	1.5	3.1	1.0	0.87	7.0	5.8	5.3
13.5	6.9	3.5	1.8	1.4	2.8	1.1	0.91	6.9	5.8	5.2
13.8	7.4	3.7	1.8	1.4	2.8	1.1	1.0	7.4	6.1	5.5
13.9	6.9	3.5	1.8	1.5	2.9	1.0	0.92	6.9	5.9	5.3
14.2	7.4	3.8	2.0	1.5	3.2	1.0	0.95	7.4	6.2	5.7
14.3	7.4	3.7	1.8	1.4	3.1	1.0	0.95	7.4	6.2	5.5
14.6	7.4	3.8	1.8	1.7	3.2	1.1	1.0	7.4	6.2	5.4
14.9	7.8	4.2	2.0	1.7	3.2	--	--	7.8	--	6.1
15.2	8.2	4.2	1.9	1.7	3.3	--	--	8.2	7.0	6.2
15.5	8.2	4.4	2.0	1.7	3.4	--	--	8.2	7.0	6.2
¹ 16.7	8.8	4.6	2.3	1.9	3.8	1.2	1.1	8.8	7.0	6.7
¹ 17.5	8.8	4.8	2.5	1.8	3.6	1.2	1.2	8.8	7.2	6.9
¹ 17.7	8.8	4.8	--	--	3.8	1.2	1.2	--	7.4	6.7
² 17.4	9.0	4.9	2.4	1.9	3.7	1.1	1.2	9.0	7.2	6.9

¹ Transformation stage.
² Juvenile.

FIN DEVELOPMENT

Our smallest specimen (5.4 mm) is undergoing flexion of the tip of the notochord and already has the adult complement of 10 superior and 9 inferior principal caudal rays (Table 2): In the next smallest larva (6.2 mm), also undergoing notochord flexion, a single procurent ray is forming in the superior and inferior series. The adult complement of 10-11 superior and 10-12 inferior procurent rays is present in larvae 13.0 mm and larger.

The pectoral fins are represented by their inconspicuous bases in the 5.4- and 6.2-mm specimens; the fins themselves are membranous, with no ossified rays. Description of the gradual acquisition of ossified rays described for pectoral fins of other species (Moser and Ahlstrom, 1970) is precluded by the gap in our series of *Scopelopsis*. Larvae 10.8 mm and larger have the adult complement of 10-11 rays in each fin.

The bases of the dorsal and anal fins are beginning to form on the 5.4- and 6.2-mm larvae, but no rays are ossifying. Larvae 10.8 mm and larger have the adult complement of 21-23 dorsal and 23-25 anal rays.

The pelvic fin buds are present in the 6.2-mm larva, and larvae 10.8 mm and larger have the adult number of 8 rays in each fin. The adipose fin is beginning to develop at 6.2 mm and is well formed by 10.8 mm.

Gill rakers and vertebrae develop later than do the fins. Gill rakers are first apparent in the 10.8-mm larva and are added gradually. On the first arch, the full complement of 7-9 epi-branchial rakers is achieved at 13.5 mm while, on the lower limb of the arch, the full complement of 15-17 rakers is present at 15.2 mm. A 10.8-mm larva already has 34 vertebral centra forming; the adult number of 37-40 vertebrae is present in larvae 12.2 mm and larger.

TABLE 2.—Meristic characters of cleared and stained larvae of *Scopelopsis multipunctatus*.

Length (mm)	Primary caudal fin rays		Secondary caudal fin rays		Branchio- stegal rays		Pectoral fin rays		Hypural elements		Gill rakers (right arch)		Anal fin rays	Dor- sal fin rays	Pelvic fin rays		Vertebrae
	Super- rior	Infe- rior	Super- rior	Infe- rior	Left	Right	Left	Right	Super- rior	Infe- rior	Upper left limb	Lower right limb			Left	Right	
5.4	10	9	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
6.2	10	9	1	1	--	--	--	--	--	1	--	--	--	--	--	--	--
10.8	10	9	9	10	8	8	11	11	4	3	4	12	24	23	8	8	34
12.2	10	9	9	10	9	9	10	10	4	3	6	12	24	22	8	8	39
13.0	10	9	10	11	10	10	10	11	4	3	6	14	23	21	8	8	38
13.5	10	9	11	12	9	9	10	10	4	3	7	14	24	22	8	8	39
13.9	10	9	10	12	9	9	11	11	4	3	7	14	25	23	8	8	39
14.3	10	9	11	12	9	10	11	11	4	3	7	14	24	22	8	8	38
15.2	10	9	11	11	10	10	11	12	4	3	8	16	24	22	8	8	39
15.7	10	9	9	11	10	10	11	10	4	3	8	15	23	22	8	8	39
17.6	10	9	10	12	10	10	10	11	4	3	8	16	24	23	8	8	39

PIGMENTATION

Scopelopsis larvae develop a distinct pattern of melanophores. The smallest larva in our series (5.4 mm) has a prominent median melanophore at the nape and a smaller melanophore embedded in the otic region at each side of the head. Another large melanophore is embedded at the ventral midline, just below the bases of the pectoral fins. An equally prominent melanophore lies above the gut, at the point where the free terminal section diverges from the body. An elliptical shield of melanophores lies above the developing gas bladder but is partially masked by the body wall musculature. A series of six evenly spaced melanophores is embedded along the ventral midline of the tail. All the melanophores that constitute this initial pattern remain throughout the larval period. The series at the ventral midline of the tail usually contains five or six melanophores in older larvae; specimens with fewer than three or more than eight were not found.

Another major area of pigmentation is visible in a 6.2-mm larva, which has two melanophores in the dorsal midline posterior to the adipose fin. In larger larvae this series extends anterior to the dorsal fin, with the usual condition being a series of three, four, or five melanophores on, or on either side of, the midline. An 11.3-mm larva has the maximum number of 10 melanophores in this series, with several of the melanophores positioned along the base of the dorsal fin.

Final additions to the melanophore pattern are in the head and caudal fin. In specimens 10.8 mm and larger, a melanophore is embedded anterior to the base of each pectoral fin, and specimens 11.3 mm and larger have one to several melanophores above the posterior region of the brain. Larvae 10.8 mm and larger have one to several melanophores embedded in the hypural region of the tail; these melanophores may lie over the superior hypurals, the inferior elements, or both. Similarly, in specimens 12.3 mm and larger, one to several melanophores may be found at the base of the caudal rays, either at the superior group, the inferior group, or both. Some specimens lack these caudal ray melanophores. A few larvae have an additional median melanophore at the junction of the hypural elements and the rays.

PHOTOPHORE DEVELOPMENT

A number of photophores develop in larvae of *Scopelopsis* in a prescribed sequence.² As in most other myctophids the Br₂ are the first to form. They are just visible in our smallest specimen (5.4 mm) and are well formed in a 10.8-mm specimen. The next to appear is the posteriormost PO pair which is just visible in the 10.8-mm larva but is well formed, although small, in

² For clarity, a diagram of the characteristic photophore groups of adult myctophids is shown in Figure 4.

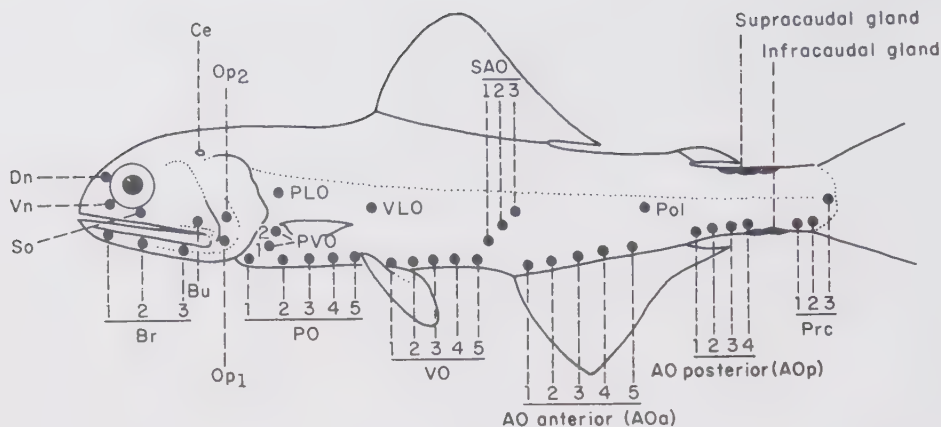


FIGURE 4.—Diagram of characteristic photophore groups of adult myctophids (modified from Nafpaktitis and Nafpaktitis, 1969 and Fraser-Brunner, 1949).

larger specimens in the series. The next to develop are the Vn; they appear anteroventral to the eye in the 11.3-mm larvae and become progressively cup-shaped as development proceeds. At the end of the larval period they are the largest photophores present. During transformation they begin to be overlain with tissue and bone so that they are difficult to see in juveniles and adults; this is doubtless why they have been overlooked by recent authors (Fraser-Brunner, 1949; Nafpaktitis and Nafpaktitis, 1969). The fourth pair of photophores to develop are the VLO; they first appear slightly posterior to, but well above, the bases of the pelvic fins in a 13.4-mm larva.

The four pairs of photophores described above are the only ones to develop until the larvae reach about 15-mm length. In a series of five larvae 14.9-15.7 mm long, a number of other photophores are beginning to appear. In the jaw region one is visible just below the terminus of each maxillary, and another is forming above and slightly anterior to the end of the maxillary. One or two others are developing in a line extending dorso-anteriad from the latter cheek organ. Dorsally on the head, a photophore is developing above the lateral margin of each olfactory lobe. In the PO series two pairs are evident, one slightly posterior to the juncture of the cleithra and another pair equidistant between

this pair and the most posterior pair, described above. A VO pair is developing midway between the bases of the pelvic fins and the anus. Farther posterior on the body, the SAO₃ are developing as are the posteriormost Prc pair.

The photophore pattern is augmented further in the three remarkable transforming specimens illustrated in Figures 2 and 3, in which the adult pattern of photophores is clearly emerging. The three represent a developmental series of which the 17.6-mm specimen is the least advanced, followed by the progressively more advanced 16.7- and 17.5-mm specimens. In the 17.6-mm specimen the previously described photophore pattern on the head is augmented by several organs below and to the rear of the eye, by a line of organs along the lower jaw, and by several on the opercle. On the body a PLO and one PVO is present at the pectoral fin base, several organs are forming above the vent, and two POL are arranged horizontally above the end of the anal fin. In addition, two horizontal lines of photophores are beginning to appear, one above and one below the lateral line. The adult photophore arrangement of *Scopelopsis* is clearly manifest in the 16.7- and 17.5-mm specimens. Photophores are beginning to cover the head in a definite pattern; some of these are considerably larger and more defined than others. On the body the many regular rows of secondary organs are emerging, al-

though the following larger and more distinct primary photophores stand out on the 17.5-mm specimen: PO₁₋₄, PVO_{1 and 2}, VLO, VO, SAO₁₋₃, POL₁₋₃, Prc.

In the 17.4-mm juvenile it is evident that the photophores on the body are on the posterior margin of each scale pocket, thus explaining their regular arrangement into horizontal rows. The specimen is partially skinned, but one can see that some body photophores remain decidedly larger than others (notably two of the PO, the VLO, and VO), while generally the distinction between primary and secondary organs is less marked. On the head, certain of the cheek photophores remain large and distinct and, additionally, the two-part Dn is now present as are the small anterior and posterior Br.

Opinion has been divided on whether or not the dichotomy of primary and secondary photophores, described above, is present in adult *Scopelopsis*. In his original description Brauer (1906) did not distinguish between primary and secondary organs. Tåning (1932) stated that some of the organs were larger than others and, moreover, made the important observation that the scales over these larger organs were equipped with a special lenslike modification typical of other myctophids. He noted that among the prominent photophores were a PLO, two PVO, a VLO, three SAO in a rather steep line, and two POL in a horizontal line. His statement, "... in fact we find all the different groups of organs which we have in all other species of the subfamily Myctophini, small, but larger than the very small organs scattered all over the body ..." was unaccompanied by an illustration. Fraser-Brunner (1949) recognized that certain photophores were more highly developed than others and termed these primary organs in contrast to the less highly developed secondary organs. He gave the following formula: "PLO above, both PVO below base of pectoral. Five PO. Five VO. Three SAO in an oblique series. AO in two series. Two POL in horizontal series. Five or more Prc." His accompanying illustration shows the basic photophore pattern but is somewhat illegible, especially in the caudal region. Nafpaktitis and Nafpaktitis (1969) could not differentiate primary and secondary photophores

in their material. Wisner (in press) employed a large series of excellently preserved specimens in his description of *Scopelopsis* and showed that the ability to differentiate primary from secondary photophores is dependent on the condition of the specimen. In specimens which had retained most of their scales he identified primary photophores as those with a lenslike modification of the overlying scale. His photophore formula and clear illustration corroborate the observations of Tåning (1932) and Fraser-Brunner (1949); further refinements include his observation of 7-10 anterior AO, 5-6 posterior AO, 4-6 Prc, 2 or 3 POL, and 3 prominent cheek photophores in a diagonal line anterior to the preopercle. Additionally he shows definitively the two-part Dn and the embedded Vn. The observations of Tåning (1932), Fraser-Brunner (1949), and Wisner (in press) along with the evidence presented herein demonstrate that certain of the multitudinous light organs of *Scopelopsis* are more highly developed than others and that these "primary organs" are arranged in a pattern that corresponds to the general pattern of other members of the family. Our observations on ontogenetic series largely confirm the arrangement of primary photophores postulated by these authors, but some of our findings suggest discrepancies that may only be clarified by further examination of undamaged adults. For example, we find only four well-developed PO and a single large VO in transforming specimens and in juveniles and adults available to us. This as well as the exact frequencies of AO and Prc series await elucidation by workers with large series of intact adults.

SYSTEMATIC RELATIONSHIPS

The efficacy of using the larval and transformation stages of lanternfishes to elucidate specific and supraspecific relationships has been clearly demonstrated (Pertseva-Ostroumova, 1964; Moser and Ahlstrom, 1970). We (Moser and Ahlstrom, 1970) showed that the genera of Myctophidae can be divided into two groups on the basis of larval eye shape—those with narrow elliptical eyes and those with round or nearly

round eyes. That these are phylogenetically natural groups is supported by Paxton (1968, 1972) who, on the basis of adult osteology and photophore arrangement, formally established the same two groups of genera as subfamilies. He grouped the 11 genera with narrow-eyed larvae into the subfamily Myctophinae and the 17 genera with round-eyed larvae into the subfamily Lampanyctinae. Further, in our paper we described the evolutionary lineages within the Myctophinae as evidenced by the structure of the larvae. Many of our conclusions agreed with those of Paxton (1968), derived from adult characters, but we differed ultimately with his distribution of the 11 myctophine genera into two tribes and with his derivation of the subfamily Lampanyctinae from an already highly evolved lineage of the subfamily Myctophinae. The larvae of the subfamily Lampanyctinae, although morphologically conservative compared with those of the Myctophinae, are useful, nonetheless, in revealing evolutionary lineages within the subfamily. The diversity of eye shape, so spectacular in the Myctophinae, is absent in the Lampanyctinae, but the eyes of many genera are distinctive because of their size, subtle but characteristic deviation from the basic rounded outline, or presence of a ventral crescent of choroid tissue. Likewise each genus of Lampanyctinae has a characteristic body shape, although the subfamily lacks the diversity of body form, so dramatic in the Myctophinae. The peculiar modifications of the paired fins, common among the larvae of Myctophinae, are generally absent in the Lampanyctinae; only in the lampanyctine genera *Lampanyctus* and *Lobianchia* do the pectoral fins attain some degree of specialization.

Three characters that are shared by the larvae of many lampanyctine genera are: 1) the sequential development of three or more pairs of early-forming photophores, 2) the development of a series of melanophores at the dorsal and at the ventral margins of the body, particularly in the tail region, and 3) the development of one or more melanophores above the brain. The sequence of development of early-forming photophores is an especially useful character that may provide a key to the elucidation of phylogenetic lineages within the Lampanyctinae. Eleven of

the 17 genera of Lampanyctinae develop such early-forming photophores and can be grouped as follows:

Group A—Br₂, PO₅, and Vn form in that sequence; fourth pair, either PLO or VLO, form later in larval period.

Scopelopsis - VLO fourth pair to form.

Notoscopelus - PLO fourth pair to form.

Lampichthys - PLO fourth pair to form.

Group B—Br₂, Vn, PLO, and PO₅ form sequentially; photophores very small.

Ceratoscopelus - all four pairs formed early in larval period.

Bolinichthys - some species develop larval photophores, as above, and others develop only the Br₂ as larvae.

Lepidophanes - Vn, PLO, and PO₅ form almost simultaneously after the Br₂; OP₁, and OP₂ form just before transformation.

Group C—Br₂, PLO, and PO₅ early-forming.

Lampadena - Br₂, PLO, and PO₅ appear sequentially; later in larval period, PO₁ and Vn form sequentially.

Lampanyctodes - Br₂, PLO, and PO₅ formed on 9.2-mm larva; smaller larvae and, consequently, information on sequence of appearance, not available.

Group D—Br₂, PO₅, and PO₁ early-forming.

Gymnoscopelus - Br₂, PO₅, and PO₁ form sequentially, early in the larval period; much later, the VO₁ and then PO₂ appear.

Diaphus - two species groups; *D. theta* and relatives form Br₂, PO₅, PO₁, VO₁, PO₂, OP₂, VO₅, PO₃, PO₄, VLO sequentially; *D. pacificus* and relatives form Br₂, PO₅, PO₁, PO₂, PVO₁, PO₃, VO₁, sequentially; photophores added gradually in *Diaphus* larvae with transformation at small size.

Lobianchia - Br₂, PO₁, PO₅, PVO₁, PVO₂ form sequentially.

The above groupings suggest phylogenetic affinities which, in most cases, are supported by other characters of the larvae and adults. The sequential development of the Br₂, PO₅, and Vn photophores is unique to the genera of Group A (*Scopelopsis*, *Lampichthys*, *Notoscopelus*). The arrangement of primary photophores, so conspicuous in the transforming specimens of *Scopelopsis*, affirms the close relationship of this genus

with *Notoscopelus* and *Lampichthys*, since the three genera are the only myctophids with horizontal POL photophores on the posterior lateral surface of the body. *Scopelopsis* and *Notoscopelus* have either two or three such photophores in a horizontal line below the lateral line, while in *Lampichthys* the two horizontal photophores form a right angle with a third POL that is placed midway between the two upper POL's and the ventral series. Other characters of the larvae substantiate the close relationship of these three genera. The larvae are similar in shape of the eye, head, and body. *Scopelopsis* and *Lampichthys* have extremely similar pigment patterns and differ only in the number and size of the melanophores in each area (Figures 1-3, 5). *Notoscopelus* differs only slightly from the other two, in its lack of a melanophore in the ventral midline below the pectoral fin and in having a prominent series of melanophores along the lateral line (Figure 6).

Characters of the adults affirm the close relationship of the three genera. *Scopelopsis* and the several species of *Notoscopelus* have the highest numbers of dorsal fin rays, 21-23 and 22-27 respectively, in the family. The Dn light organ at the anterodorsal margin of the orbit is composed of two contiguous structures in *Scopelopsis* and *Notoscopelus*; it consists of a small photophore, with a margin of black pigment, dorsal to a larger opaque mass of tissue that lacks marginal pigment. In *Lampichthys* a mass of black tissue lies below the opaque luminous tissue, which extends posteriad over the entire dorsal surface of the orbit. *Scopelopsis* is covered entirely by small secondary photophores, as is the body of *Lampichthys*. Such photophores are absent from the head of *Lampichthys*; however, the four or five prominent cheek photophores of *Lampichthys* are comparable to those of *Scopelopsis*. A single opaque patch of luminous tissue lies below each pectoral fin base in *Scopelopsis*. In *Lampichthys*, a luminous patch is present in exactly the same position; however, several additional patches are present on the lateral surfaces of the body. In *Notoscopelus*, luminous patches are much more extensive, although the prominent patch below the base of each pectoral fin is present in all species of the genus.

The sequential development of the Br₂, Vn, PLO, and PO₅ is unique to the genera in group B (*Ceratoscopelus*, *Lepidophanes*, *Bolinichthys*); this, along with the small size of the photophores, and their early appearance, points to close relationship of the three genera. The larvae of some species of *Bolinichthys* are an exception, since they develop only the Br₂. Other characters of the larvae, such as a similarity in body shape and a general paucity of pigment, also suggest the close relationship of the three genera (Figures 7, 8, 9). Paxton (1972) has pointed out a number of osteological characters of the adults that link the three genera, and the similarity in the arrangement of luminous patches among species of the three genera is well established in the literature.

The larvae of *Lampadena* and *Lampanyctodes* (group C above) develop the Br₂, PLO, and PO₅. The PLO photophores become conspicuously developed on small larvae of *Lampadena* soon after the formation of the Br₂ pair; the PO₅ pair appear shortly thereafter (Figure 10). The Vn pair is later-forming and may be preceded by the PO₁ pair, or the two pairs may form simultaneously. The sequence of development of early-forming photophores on *Lampanyctodes hectoris* has not been fully established. The Br₂, PLO, and PO₅ pairs were well developed on the smallest larva (9.2 mm) available for study (Figure 11). A 14.5-mm transforming specimen of *Lampanyctodes* had 13 pairs of photophores developed, including the Vn and PO pairs. Even so, the only genera with this combination of three early-forming photophores are *Lampadena* and *Lampanyctodes*. Also, the larvae of the two genera are similar in body shape and in pigmentation.

The larvae of *Gymnoscopelus* (group D above) form the Br₂, PO₅, and PO₁ early (Figure 12). Later in the protracted larval period, the VO₁ and then PO₂ appear. In some species (e.g., *G. aphyia*) the larvae reach a length of 28 mm and are the largest of all myctophid larvae. *Diaphus* and *Lobianchia* also develop the Br₂, PO₅, and PO₁ early in the larval period and are included in group D. This, however, is virtually the only larval character that the two genera share with *Gymnoscopelus*. They develop photophores grad-

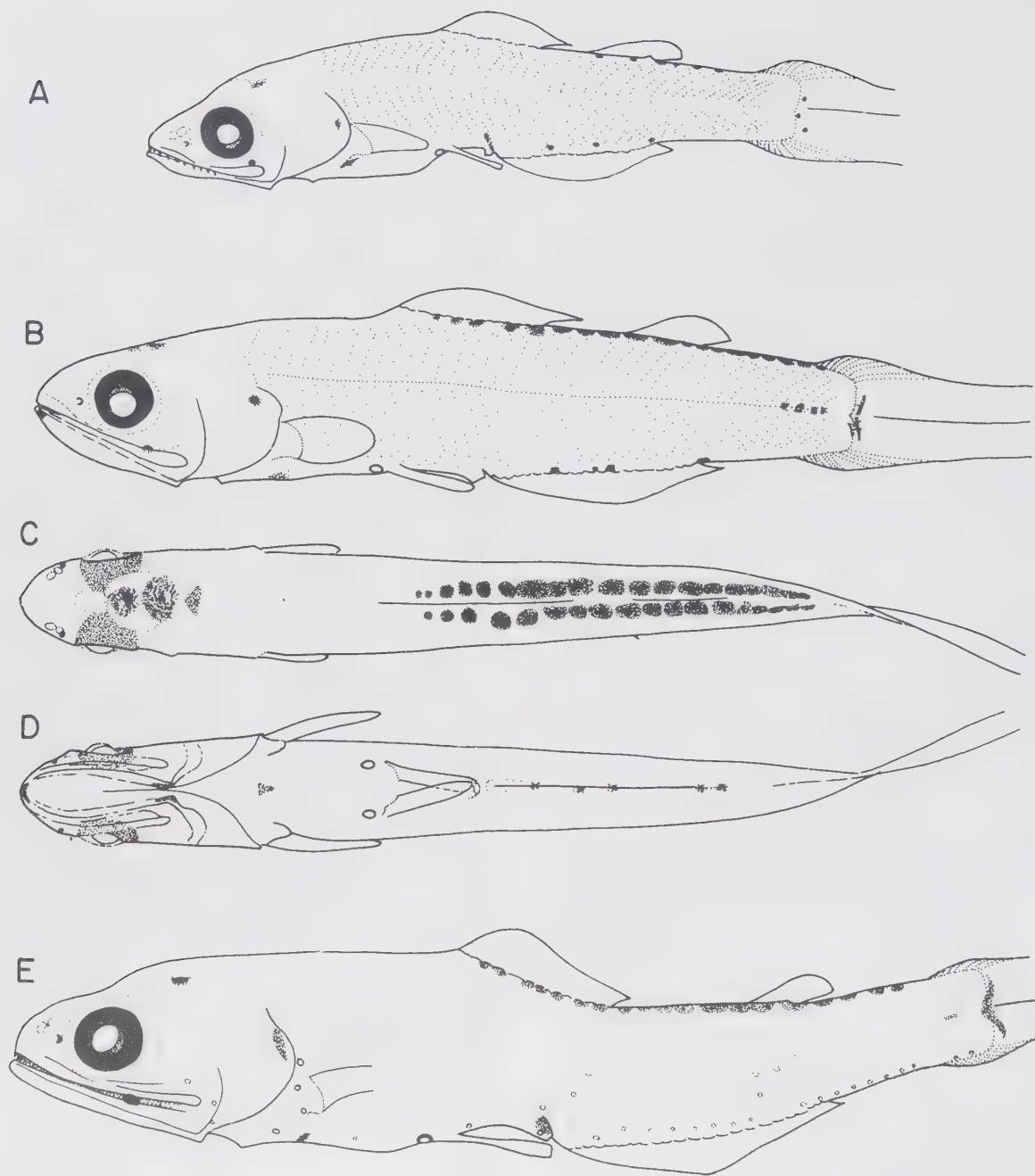


FIGURE 5.—Developmental stages of *Lampichthys procerus* (Brauer).—A, 11.4-mm larva, U.S. NS *Eltanin* Station 314; B, 14.5-mm larva, R.R.S. *Discovery* Station 100c; C, 14.5-mm larva dorsal view; D, 14.5-mm larva, ventral view; E, 20.3-mm transformation stage, U.S. NS *Eltanin* Station 306.

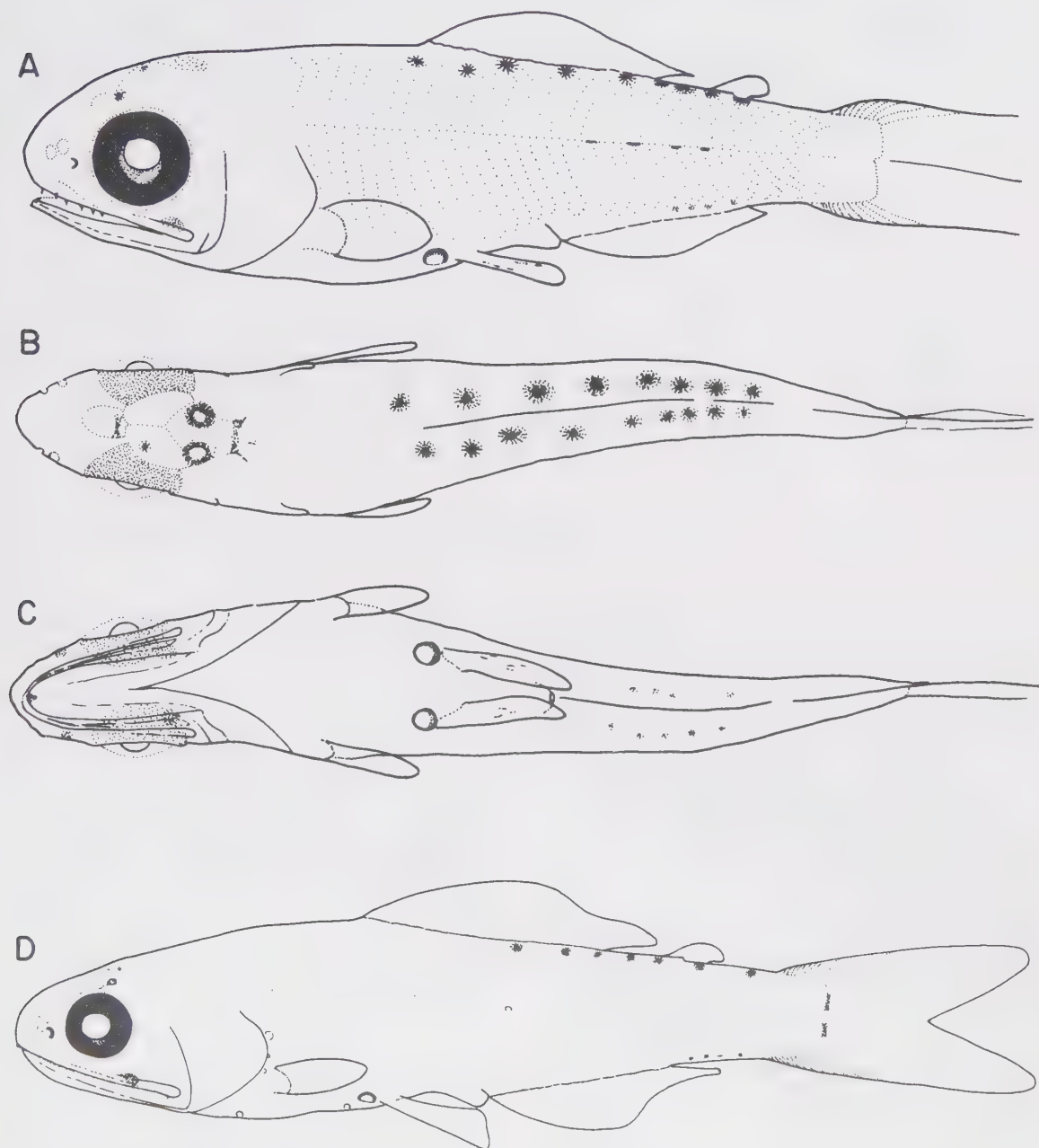


FIGURE 6.—Developmental stages of *Notoscopelus resplendens* (Richardson).—A, 11.2-mm larva, CalCOFI 6310-97.90; B, 11.2-mm larva, dorsal view; C, 11.2-mm larva, ventral view; D, 21.0-mm transformation stage, CalCOFI 6207-90.110.

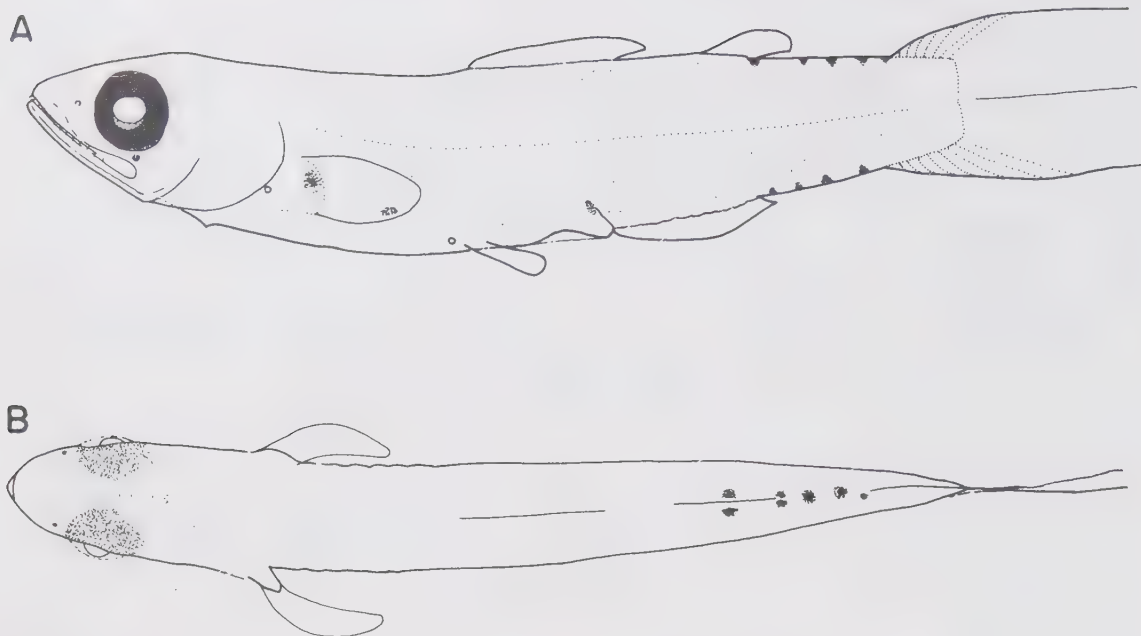


FIGURE 7.—Developmental stage of *Ceratoscopelus maderensis* (Lowe).—A, 13.4-mm larva, RV *Meteor* Station 72-39; B, 13.4-mm larva, dorsal view.

usually during the larval period, which appears to be rather short; most species transform within the size range of 10-15 mm. Also, the characteristic shape and basic pigment pattern of larval *Diaphus* and *Lobianchia* are distinctively different from those of *Gymnoscopelus*. In shape and pigmentation, the larvae of *Gymnoscopelus* resemble most closely those of group A (*Scopelopsis*, *Lampichthys*, *Notoscopelus*).

Of the remaining six genera of the subfamily Lampanyctinae, *Notolychnus* develops no photophores during the larval period, and *Lampanyctus*, *Triphoturus*, and *Stenobranchius* develop only the Br₂ as larvae. Our developmental series of *Taaningichthys* is incomplete; however, larvae up to 18 mm long have no photophores. In our largest larva (19.3 mm), the PO₅ are just beginning to develop. The larvae of this genus are apparently neustonic, and this may have an important influence on photophore development. They are most similar to larvae of *Lampadena* in pigment pattern but are much more slender. The small larvae of *Taaningichthys minimus* are unusual in having a conspicuous series of embedded

melanophores above the vertebral column (Figure 13). The larvae of *Hintonia* are as yet unknown.

From our studies of the larvae of the subfamily Lampanyctinae, the genera *Scopelopsis*, *Lampichthys*, *Notoscopelus*, *Gymnoscopelus*, *Ceratoscopelus*, *Bolinichthys*, *Lepidophanes*, *Lampanyctodes*, *Lampadena*, and *Taaningichthys* emerge as a natural assemblage based on sequence of photophore development, morphology, and pigmentation. The grouping of these genera as a phylogenetic unit conflicts with the phylogenetic scheme proposed by Paxton (1968, 1972). His arrangement of the 17 genera of the subfamily Lampanyctinae into four tribes, based on a combination of adult osteology and photophore pattern, is shown in Figure 14. We agree that *Notolychnus valdiviae* has an ample array of unique adult and larval characters to warrant its placement in the monotypic tribe Notolychnini. Likewise we concur with the establishment of a separate tribe Diaphini for *Diaphus* and *Lobianchia*, two genera with a dis-

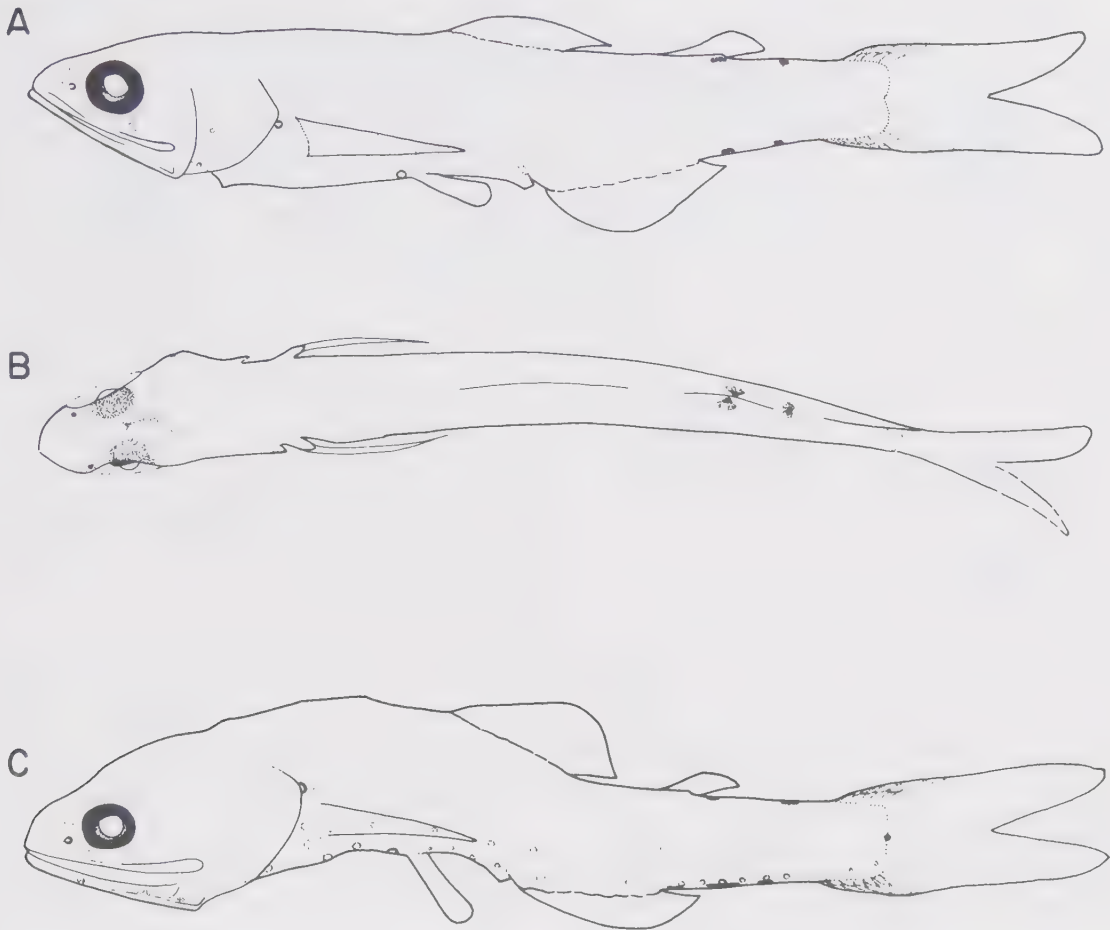


FIGURE 8.—Developmental stages of *Lepidophanes guentheri* (Goode and Bean).—A, 13.5-mm larva, R.S. Dana Station 3998X; B, 13.5-mm larva, dorsal view; C, 12.7-mm transformation stage, R.S. Dana Station 3998X.

tinct facies of adult and larval characters. Paxton placed the remaining 14 genera into two tribes, the Lampanyctini and Gymnoscopelini. On the basis of larval characters, we cannot concur with his distribution of genera among the two tribes. He included eight genera (*Lampanyctus*, *Stenobranchius*, *Triphoturus*, *Ceratoscopelus*, *Lepidophanes*, *Bolinichthys*, *Taaningichthys*, and *Lampadena*) in the tribe Lampanyctini and restricted the tribe Gymnoscopelini to six genera (*Gymnoscopelus*, *Lampanyctodes*, *Notoscopelus*, *Lampichthys*, *Scopelopsis*, and *Hintonia*). Paxton found no single character that

would differentiate any of the four tribes from all others in the subfamily and relied on a combination of osteological and photophore characters to define the tribes. His most trenchant characters separating the Gymnoscopelini from the Lampanyctini were the presence of a supra-maxillary bone in the Gymnoscopelini and its absence in the Lampanyctini and the presence of a Dn photophore in the former and its absence in the latter.

Our findings in the larvae suggest a different distribution of genera for the two tribes. On the basis of larval characters described earlier

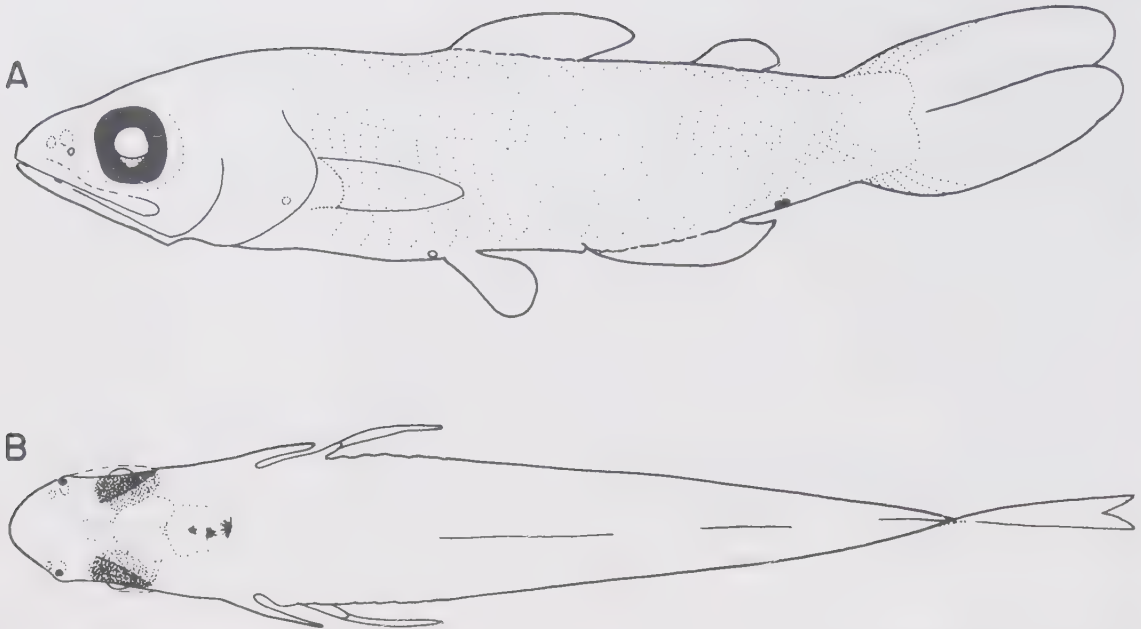


FIGURE 9.—Developmental stage of *Bolinichthys* sp.—A, 10.6-mm larva, R.R.S. *Discovery* Station 702; B, 10.6-mm larva, dorsal view.

we would enlarge the tribe Gymnoscopelini to include *Ceratoscopelus*, *Lepidophanes*, *Bolinichthys*, *Lampadena*, and *Taaningichthys* as well as the six genera assigned to the tribe by Paxton. We would restrict the tribe Lampanyctini to *Lampanyctus*, *Stenobranchius*, and *Triphoturus*, three genera with distinctive larvae that develop only the Br₂ photophores, and are characterized by an abrupt transformation from larva to juvenile. Our suggested modification of Paxton's scheme is shown in Figure 15.

Even though we propose a different distribution of genera in the tribes Gymnoscopelini and Lampanyctini, there is a striking concordance between our groupings of related genera and Paxton's, derived from quite different criteria. For example, both methods suggest a close relationship for *Scopelopsis*, *Lampichthys*, and *Notoscopelus* as well as for *Ceratoscopelus*, *Lepidophanes*, and *Bolinichthys*.

It should be noted that the heaviest development of accessory luminous tissue occurs in the genera we place in the tribe Gymnoscopelini and that such luminous tissue is best developed on

Ceratoscopelus, *Bolinichthys*, *Lepidophanes*, *Lampichthys*, and *Hintonia*. On *Ceratoscopelus townsendi* and various species of *Bolinichthys*, conspicuous patches of luminous tissue form on the head between the orbits, especially in adult males. In these genera there may be a direct relation between the absence of the Dn photophores and the presence of accessory luminous tissue on the head.

A PROPOSED THEORY FOR THE EVOLUTION OF PHOTOPHORE PATTERN IN MYCTOPHIDAE

Perhaps the most intriguing result of our studies of larvae of the tribe Gymnoscopelini is a theory for the evolution of photophore pattern in lanternfishes. The only previous theory was proposed by Bolin (1939) and fully developed by Fraser-Brunner (1949). Fraser-Brunner (1949) postulated an hypothetical ancestral myctophid with a pair of continuous photophore rows on the ventral margin, beginning with the

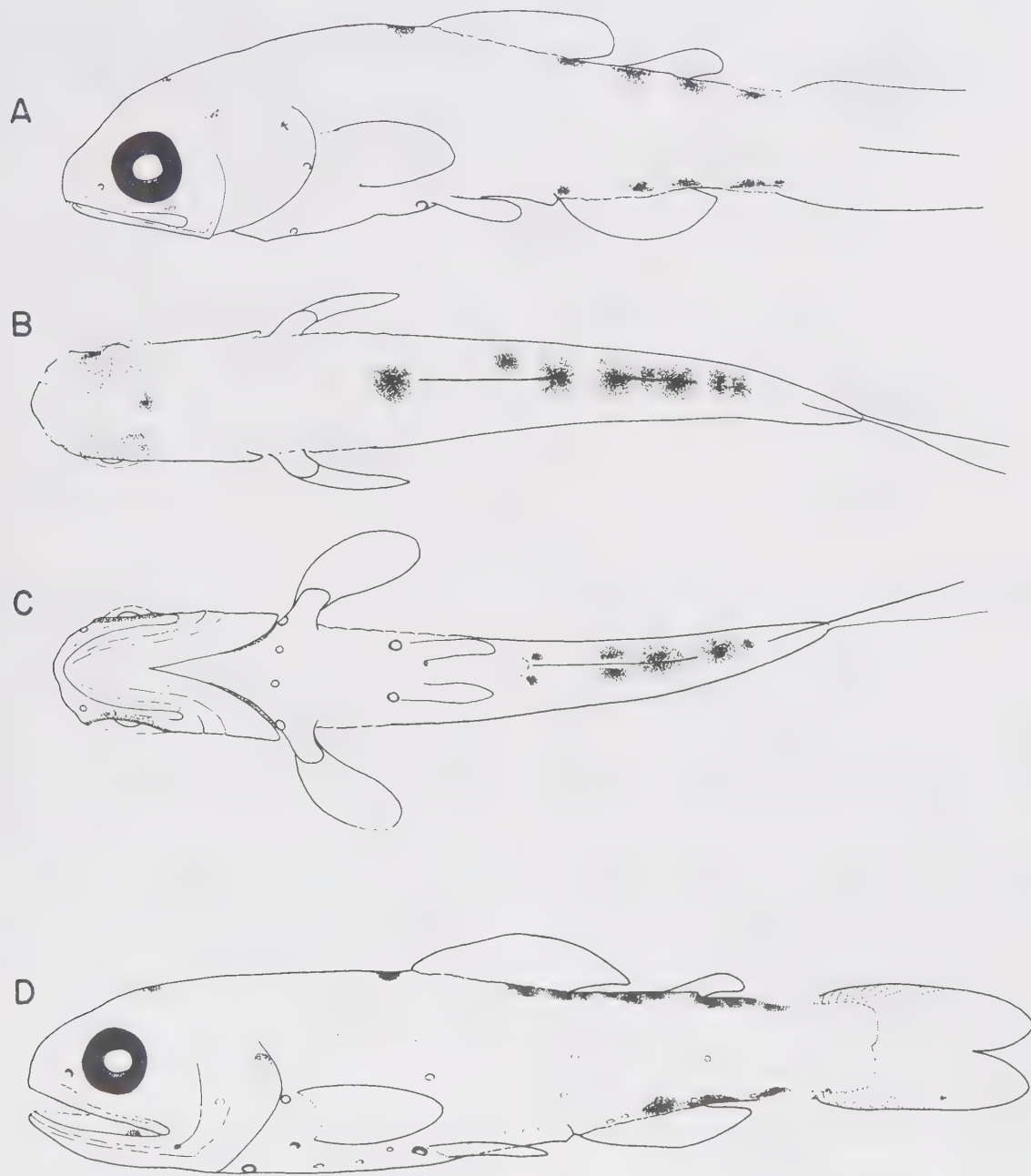


FIGURE 10.—Developmental stages of *Lampadena urophaos* Paxton.—A, 13.4-mm larva, CalCOFI 5011- S-T3; B, 13.4-mm larva, dorsal view; C, 13.4-mm larva, ventral view; D, 19.6-mm transformation stage, CalCOFI 6210-117.90.

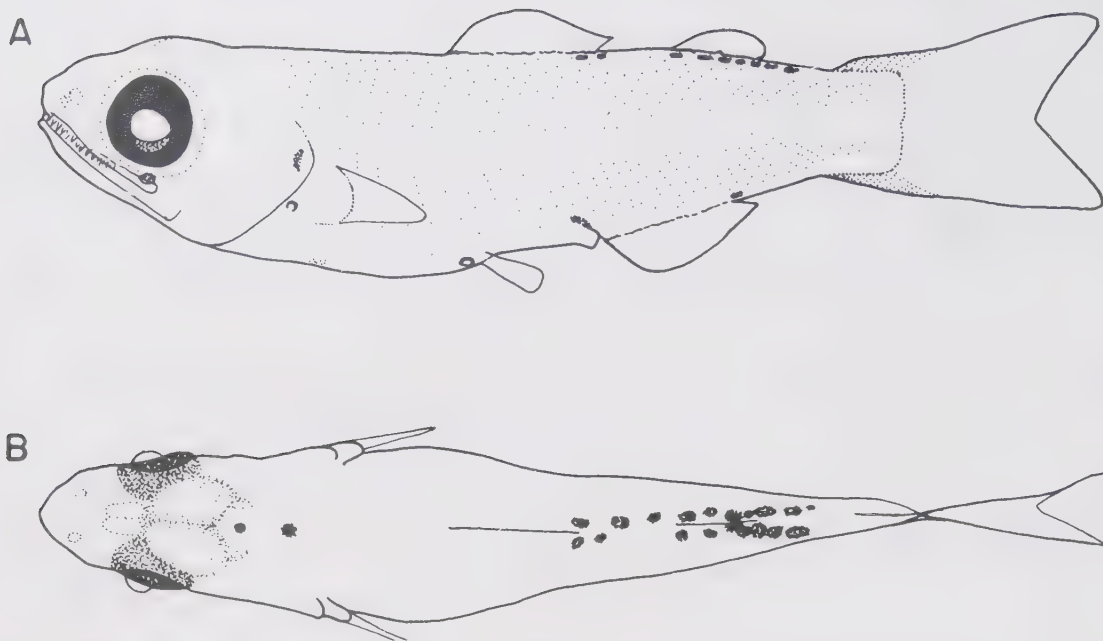


FIGURE 11.—Developmental stage of *Lampanyctodes hectoris* (Günther).—A, 9.2-mm larva, R.R.S. *Discovery* Station 1374; B, 9.2-mm larva, dorsal view.

most ventral jaw photophore (Br_3) and extending posteriad to the tail. Above these ventral rows on each side was a lateral row that extended from the middle jaw photophore (Br_2) posteriad to the anus. A third row began with the upper jaw photophore (Br_1) and ended with the upper opercular photophore. Fraser-Brunner proposed that the photophore patterns of all extant lanternfish species were derived by upward migration of certain photophores on the ventral and lateral rows of the ancestral form. His chief evidence for such upward migration was that, in present-day myctophids, certain lateral photophores, such as the posterior two SAO and the POL, lie above gaps in the ventral series. These gaps were presumably produced by the upward migration of photophores to the lateral position they now occupy. He found other indirect evidence in the presence of small modified scales which overlie certain of the lateral photophores in some species. Since these scales were out of the meristic lines of the larger scales, Fraser-Brunner concluded that they were scales that

had been "taken with" the photophores during their upward migration.

Fraser-Brunner's (1949) hypothesis has remained unchallenged or at least tacitly accepted by workers up to the present; however, we believe that it contains a number of deficiencies which warrant an alternative theory for the evolution of the photophore pattern in lanternfishes. Firstly, we believe that the presence of certain lateral photophores above gaps in the ventral row is tenuous indirect evidence of migration, since there are many examples of lateral photophores lying directly above photophores in the ventral series, and there are equally numerous examples of gaps in the ventral series with no overlying photophores whatsoever. Further, we find the presence of small specialized scales over certain of the lateral photophores to be inconclusive evidence of upward migration from the ventral series, since some lateral photophores are overlain by normal-sized scales that are aligned with the other scales in their row. Also, if a photophore had carried its scale with it dur-

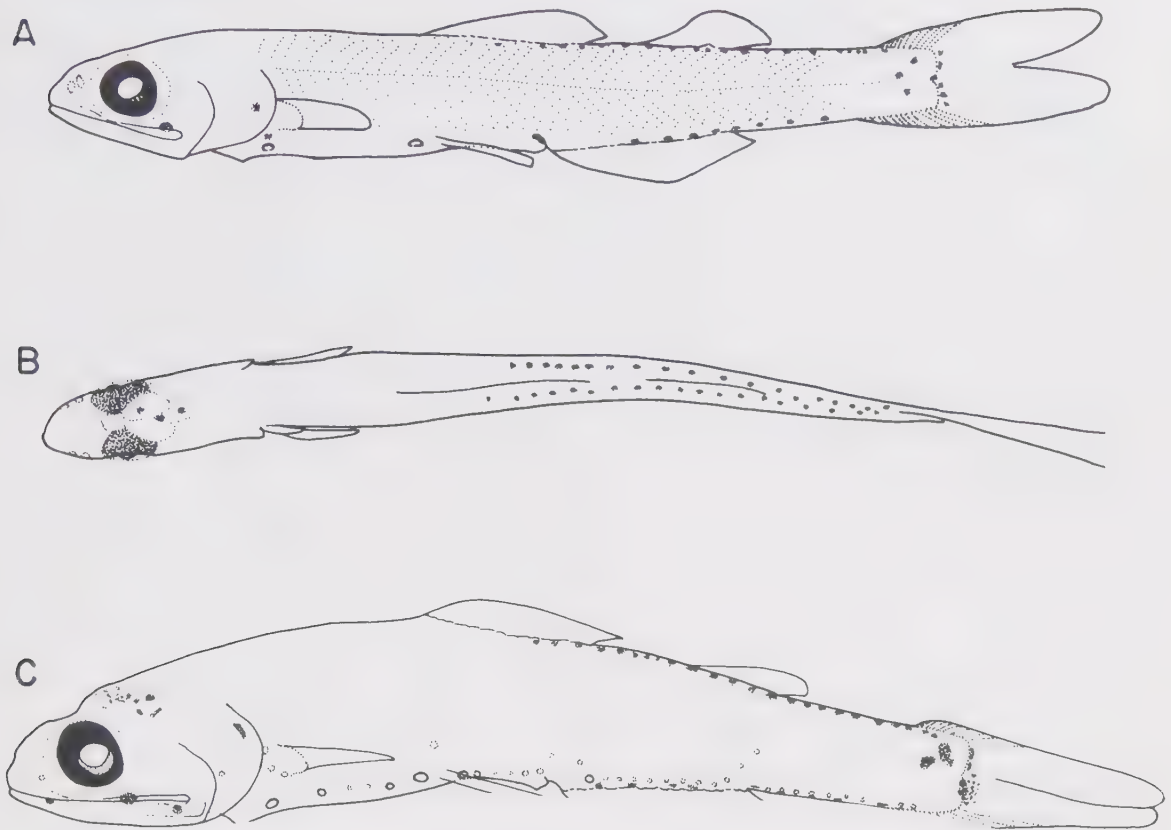


FIGURE 12.—Developmental stages of *Gymnoscopelus aphyia* Günther.—A, 23.5-mm larva, U.S. NS *Eltanin* Station 319; B, 23.5-mm larva, dorsal view; C, 27.7-mm transformation stage, U.S. NS *Eltanin* Station 1341.

ing its upward migration, one might expect a comparable deletion or modification at its origin in the ventral scale row. There is none. Another major deficiency in the theory is its inability to explain the photophore pattern of a species such as *Notolychnus valdiviae* which has four pairs of photophores near the dorsal midline. If derived from the ventral series, the dorsal photophores would be supplied by peripheral nerves of the ventral or medial spinal rami that would have to extend dorsad across the horizontal septum; such an arrangement seemed so unlikely for species with photophores above the lateral line that we traced the nerve supply to such photophores in *Triphoturus mexicanus*, *Bolinichthys* sp., and *Notolychnus valdiviae*. In *T. mexicanus* the VLO, SAO₃, POL₂, and Prc₃

lie above the lateral line, and in *Bolinichthys* the latter three photophores lie above the line. These light organs are supplied by a branch of the lateral vagus nerve, the superficial lateral-line nerve. In *Notolychnus* the VLO, SAO₃, POL₂ and Prc₂ lie extremely high on the body near the dorsal midline. The VLO and SAO₃ are supplied by the dorsal ramus of the lateral vagus nerve. The nerve supply to the POL₂ was difficult to determine but appeared also to be the dorsal ramus of the lateral vagus nerve. The Prc₂ is innervated by the superficial lateral-line nerve.

Ray (1950), in her detailed study of the peripheral nervous system of *Stenobranchius leucoparus*, showed that all body photophores, except three pairs, are supplied by ventral rami of spinal nerves. The exceptions, SAO₃, POL, and Prc₄,

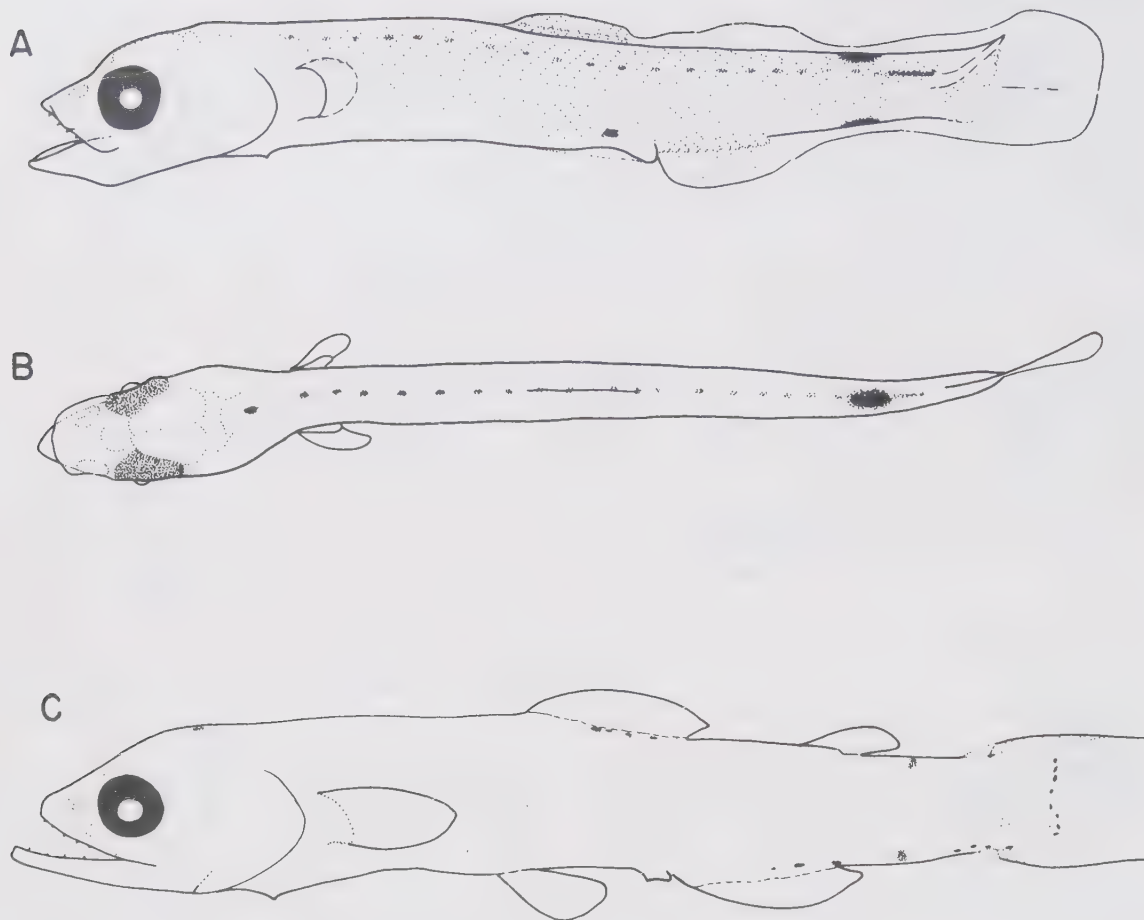


FIGURE 13.—Developmental stage of *Taaningichthys mininus* Tåning.—A, 7.3-mm larva, Hawaii Institute of Marine Biology, China Hat Series 3; B, 7.3-mm larva, dorsal view; C, 14.4-mm larva, SIO-FCRG Cruise 71-2.

are innervated by medial rami of spinal nerves; however, the first two of these each receive a small ramulus from a ventral spinal ramus. Ray believed that the innervation of lateral body photophores by ventral components of spinal nerves supported Bolin's (1939, p. 131-132) suggestion that lateral body photophores were derived by upward displacement of certain photophores from a single pair of ventral photophore rows. In lanternfish, such as *T. mexicanus*, *Bolinichthys*, and *Notolychnus*, the photophores which lie above the lateral line have always been considered homologous to their counterparts that lie below the line in other genera. Our finding

of a cranial nerve supply for photophores above the lateral line in *T. mexicanus*, *Bolinichthys* sp., and *Notolychnus* casts considerable doubt on the theory that these photophores could have arisen from upward displacement, "from a primitively ventral and strictly linear series" (Bolin, 1939, p. 131-132) or even from "two ventrally located, parallel series of photophores, such as we find in *Vinciguerria*" (Bolin, 1939, p. 97).

An alternative hypothesis for the evolution of photophore patterns became apparent to us when studying the transforming stages of *Scopelopsis* (Figures 2, 3). It is obvious that in these specimens, the so-called primary photophores

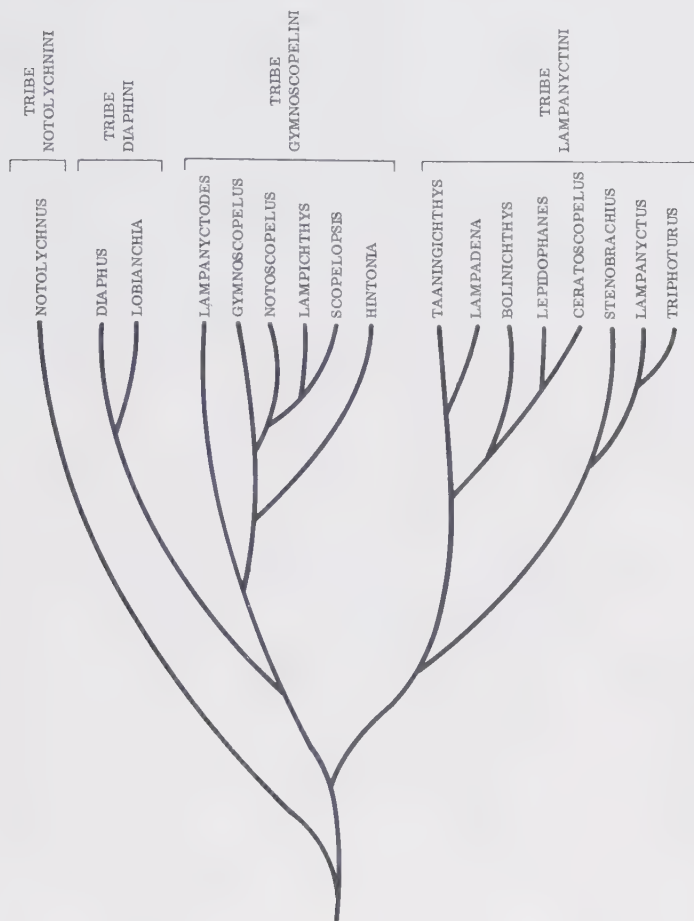


FIGURE 14.—Dendrogram of Paxton's (1968, 1972) arrangement of genera and tribes in the subfamily Lampanycetinae.

take their places very properly in the horizontal lines of smaller secondary photophores that cover the body. In these remarkable specimens, the primary photophores appear merely as enlarged members in the meristic series of light organs. Accordingly, it is tempting to speculate that this reflects a possible ancestral stage in the evolution of myctophid photophore patterns. We postulate that the archetypal pattern of light organs in lanternfishes was a generalized arrangement consisting of a single unspecialized photophore at the posterior margin of each scale pocket and a series of similar photophores distributed over the head. The progressive enlargement and specialization of certain photophores of the generalized pattern and concurrent diminution or loss of the "secondary" photophores

would seem a propitious mechanism for adaptation and subsequent species diversification. The enlargement of photophores in the ventral midline to form a pair of longitudinal rows was universal in the family. Clarke (1963) suggested that these downward oriented photophores emit a continuous light of ambient wavelength which conceals the fish by breaking up its silhouette, that would otherwise be easily detected by predators hunting from below. This and other theories for the universality of the ventral photophore rows are discussed by McAllister (1967). The placement of the ventral and lateral photophores in a pattern unique to each species is an obvious mechanism for species recognition and reproductive isolation (Harvey, 1952, 1957; Marshall, 1954; Bolin, 1961).

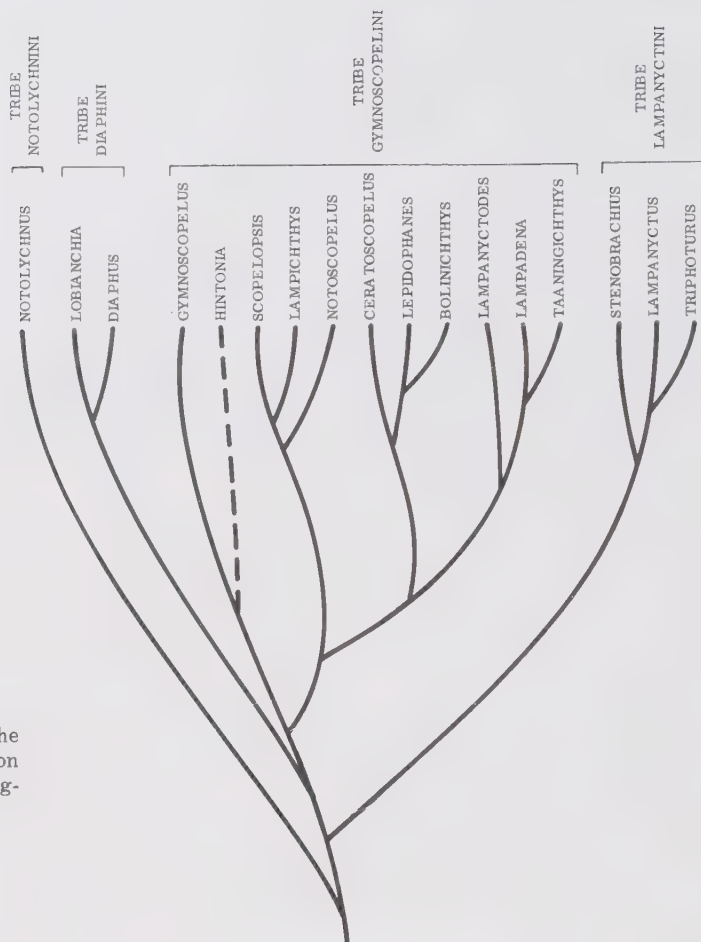


FIGURE 15.—Dendrogram showing the generic relationships and tribal division of the subfamily Lampanyctinae as suggested by larval characters.

Whatever were the adaptive forces that marshalled the light organs of myctophids into specific patterns, we believe that the ancestral myctophids had unspecialized photophores distributed over the head and body (one at the margin of each scale pocket) and that the specific patterns were derived by enhancement of some photophores and the concomitant deletion of others. Among the 28 known genera of myctophids are six (*Scopelopsis*, *Hintonia*, *Lampichthys*, *Bolinichthys*, *Lepidophanes*, and *Lampanyctus*) in which at least some species have minute photophores on the body, in addition to the typical pattern of primary photophores. The minute photophores may occur at every scale pocket (e.g., *Scopelopsis*) or may be restricted to a certain region of the body (e.g., *Hintonia*). Typi-

cally, those species with such minute photophores also have one or more head photophores that are lacking in most other myctophids. Previous workers have considered the minute photophores of these genera to be secondary structures, which have evolved after the primary organs; however, we believe that they reflect an ancestral stage in the evolution of photophore pattern. We believe that *Scopelopsis* most closely approximates the photophore pattern of ancestral myctophids since the distinction between "primary" and "secondary" organs is less apparent than in the other genera retaining secondary photophores. Moreover, every photophore position described for lanternfishes has its counterpart in *Scopelopsis*, and we find that every known myctophid photophore pattern can be generated

by enhancement of selected photophores of this species. Such a mechanism for the evolution of photophore pattern seems much less cumbersome than the theory of upward migration of photophores from the ventral series. The minor upward displacement of some ventral photophores may be a plausible explanation for the slightly arched AO and VO rows found in some myctophids but, for reasons outlined above, we find it improbable that such a mechanism could be responsible for the profoundly diverse photophore patterns of contemporary lanternfishes.

ACKNOWLEDGMENTS

Much of the background and many of the specimens for this study were obtained during a research leave spent at the Zoological Museum, Copenhagen and the British Museum (Natural History), London. We would like to thank Dr. E. Bertelsen, Marine Biological Laboratory, Charlottenlund, Denmark, and Dr. Jørgen Nielsen, Zoological Museum, Copenhagen, for the opportunity to examine the specimens of the Danish Oceanographic Expeditions. Dr. N. B. Marshall provided specimens of the *Discovery* expeditions and working space at the British Museum. Other essential *Discovery* specimens were made available by Drs. Peter M. David, National Institute of Oceanography, Wormley, England, and N. A. Macintosh, Whale Research Unit, British Museum. Drs. Richard McGinnis and Basil Nafpaktitis, University of Southern California, provided specimens from the cruises of the U.S. NS *Eltanin* as well as data from their extensive studies on lanternfish. Mr. Robert Wisner, Scripps Institution of Oceanography, furnished specimens of *Scopelopsis multipunctatus* and unpublished data on that species. Dr. Walter Nellen, Institut für Meereskunde, Kiel, provided specimens of *Ceratoscopelus maderensis*, and Dr. John M. Miller, Hawaii Institute of Marine Biology, provided specimens of *Taaningichthys minimus*. Technical assistance during this study was provided by Elaine Sandknop and Elizabeth Stevens, National Marine Fisheries Service, La

Jolla, Calif. Figure 4 was prepared by Kenneth Raymond, the remaining illustrations by the senior author.

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Chapter 6

DEVELOPMENT AND USES OF FACILITIES FOR STUDYING TUNA BEHAVIOR

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I. INTRODUCTION

Tunas are pelagic fishes of several genera† belonging to the family Scombridae. They are fished commercially and recreationally in the temperate and tropical seas of the world. Sizes of adult tunas range from less than a kilogram (e.g., *Auxis rochei*) to over 400 kg (e.g., *Thunnus thynnus*).

Accumulation of knowledge on the behavior of tunas was slow and haphazard before the 1950s, but has accelerated since then. In 1951, the HL (Bureau of Commercial Fisheries Biological Laboratory in Honolulu, Hawaii), known then as the Pacific Oceanic Fishery Investigations, contracted with researchers at the University of Hawaii to undertake studies of the behavioral responses of tunas to assorted stimuli. These experiments required the establishment of tunas in captivity. This feat was successfully accomplished for the first time in 1951. In the following years, techniques and methods for capturing and maintaining tunas in captivity were improved, and tanks were constructed especially for studying tuna behavior. In the mid-1950s, development of facilities to observe tunas underwater at sea was started. Significant advances in studies of tuna behavior have been made owing to observations and experiments made at sea and ashore with these facilities.

Reviews of tuna behavior have been made by several authors. Tester

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† Species of the following genera have been included as tunas in this paper: *Thunnus*, *Euthynnus*, *Katsuwonus*, *Auxis*, and *Sarda*.

(1959) summarized the studies he and his colleagues conducted from 1951 through 1956 on the responses of tunas to stimuli. Magnuson (1963) reviewed the literature on tuna behavior and physiology. Behavioral studies that were being conducted at HL were described by Magnuson (1964b). A popularized account of the work at HL was given by Manar (1965). Nakamura (1969a) has summarized observations on tuna behavior made at sea.

The purpose of this chapter is to present a history of the development of the techniques and facilities for studying tuna behavior, a statement of the problems and questions that prompted their development, and an account of the uses to which they were put. Most of the facilities and methods were developed at HL.

II. OBSERVATIONS AND RESEARCH AT SEA

Observations of tuna behavior at sea before 1957 were made only when opportunity afforded, usually from the deck of a boat—particularly boats used in fishing for tunas by pole and line. In this method, tunas are attracted to the boat by throwing overboard live bait, which is kept aboard in bait-wells. The tunas are then caught with pole and line (Yoshida, 1966). Various aspects of feeding, schooling, swimming, reactions to stimuli, behavior in relation to environmental features, and associations with other organisms and objects have been learned by observing from the decks of boats (Nakamura, 1969a).

The need to learn more about tuna behavior by observing tunas in their own environment became more and more apparent to biologists at HL in the early 1950s. Answers to such questions as the effectiveness of various species of bait, the possibility of controlling tuna behavior by manipulating fishing conditions, reactions elicited in tunas by actions of the bait, the efficacy of gear, the necessity for live bait, were difficult to obtain without going below the sea surface to observe.

The first attempt to observe tunas underwater during fishing was made in 1957. A steel ladder was lowered and secured to the side of HL's research ship *Charles H. Gilbert*. An observer descended, so that his head was about 0.5 m below the surface. He wore a regulator with an air hose attached to a cylinder of compressed air on the deck of the ship. He faced aft and observed tunas which had been attracted to the stern of the ship with live bait. This method had some notable disadvantages: the ship's speed had to be greatly reduced, observations could be made only in calm water, the observer had a difficult time keeping his purchase on the ladder and on his face mask and mouthpiece against the current, and the observer's view was often obstructed by bubbles (Strasburg and Yuen, 1960b). Subsequently,

a protective shield was built around the ladder, providing sufficient freedom to photograph.

Despite the shield, the ladder was unsatisfactory. The mouthpiece and regulator were bothersome, and communication with the ship's personnel was crude, to say the least (prearrangements were made to signal changes of events by pounding on the ship's hull). Use of this ladder did convince us, however, that observing tuna behavior underwater was feasible. Plans were therefore developed for a structure that would permit the observer to remain in air but still be below the sea surface and that would permit voice communication.

A retractable overside caisson (Fig. 1) was built in 1958 (Strasburg



Fig. 1. The retractable caisson.

and Yuen, 1960b). The caisson was a tube about 3.5 m long. It was large enough to permit one person to observe and photograph through ports about 1–1.5 m below the surface of the sea. When not in use, the caisson was raised out of the water with block and tackle. Later, the tube was extended to prevent water from splashing in over the top, the ports were enlarged to permit a wider field of visibility, and a winch was installed for lowering and raising it.

Use of the caisson was described by Strasburg and Yuen (1960a) and Strasburg (1959). They observed the behavior of skipjack tuna (*Katsuwonus pelamis*) under varying fishing conditions, such as when water sprays were turned on and off, when live and dead bait were chummed, when the rate of chumming was altered, when different species of bait were chummed, when body fluids from dead skipjack tuna were poured into the water, and when noise was presented to the tuna. Changes in schooling behavior, feeding behavior, coloration, and abundance were recorded during the experiments.

A serious disadvantage in using the caisson was the poor visibility in



Fig. 2. The stern observation chamber of the *Charles H. Gilbert*.



Fig. 3. School of skipjack tuna (*Katsuwonus pelamis*) photographed from stern chamber.

the after direction caused by bubbles in its wake. To overcome this problem, installation of underwater viewing ports in the hull of the *Gilbert* was proposed. The location of these ports as far astern as practicable seemed desirable, since fishing was at the stern.

After problems involving reductions of fuel storage, effect on ship's speed and steerage, turbulence, etc., were considered, an observation chamber was installed in 1959 on the port quarter just forward of the propeller (Fig. 2). Dimensions and details of construction have been provided by Akana *et al.* (1960), Strasburg and Yuen (1960b), and Mann (1961).

The stern chamber consists of a streamlined semicylindrical shell. Two ports permit observations from about 2 m below the sea surface directly below one of the fishing racks. Although the chamber can accommodate two persons, only one can observe comfortably in the semicylinder. The entrance is on the after bridge deck. A blower system provides ventilation. Communication is via a sound-powered telephone with headsets. The headsets help to block out much of the noise generated by the ship's machinery. Visibility is excellent and unimpeded by bubbles (Fig. 3).

The stern chamber was used during additional experiments on variation of fishing conditions. Strasburg (1961) noted a relation between diving frequency of schools of skipjack tuna and the presence of certain species of prey in stomachs of fish caught from these schools. Yuen (1969) observed catch rates, rates of attack on bait, and numbers of tunas attracted to the

vessel during the experimental fishing. The stern chamber has also been used to study the behavior of different species of bait and the behavior of tunas in response to the behavior of the bait (unpublished).

Schooling behavior, swimming behavior, and coloration of tunas have been observed and recorded from the stern chamber. Banded color phases of skipjack tuna (and also dolphin, *Coryphaena hippurus*) were observed and photographed by Strasburg and Marr (1961). Motion pictures taken from the chamber of yellowfin (*Thunnus albacares*) and skipjack tunas were analyzed to study schooling behavior (Yuen, 1963) and to determine swimming speeds (Yuen, 1966).

Although the stern observation chamber permits excellent observations of tuna behavior during fishing, it does not permit observations of tuna schools ahead of the ship. An observation chamber in the bow of the ship seemed desirable for observing while sailing up to and through schools of tuna or while following them.

A bow chamber (Fig. 4) was installed in the *Gilbert* in 1960 (Akana *et al.*, 1960; Strasburg and Yuen, 1960*b*; Mann, 1961). To do so, the bottom of the bow was reshaped into a bulbous form to provide space for an observer.



Fig. 4. The bow observation chamber of the *Charles H. Gilbert*.

Three ports were provided for viewing straight ahead and to both sides from about 2 m below the waterline.

The bow chamber comfortably accommodates one observer. Access is from the forecastle. The chamber is ventilated by a forced-draft system. As in the stern chamber, a sound-powered telephone is used for communication.

Soon after the bow chamber was constructed, Yuen (1961) had opportunities to observe and film bow wave riding by porpoise (*Tursiops* sp.). The method of bow wave riding by porpoises was the subject of a controversy among scientists at the time. Yuen settled the matter by describing "the method the (porpoises) themselves seem to consider proper."

The bow chamber has been used to observe the effectiveness of gill nets after skipjack tuna were attracted toward the net with live bait (unpublished). Most of the tuna evaded the net, which was clearly visible from about 20 m. A few skipjack tuna were seen to swim into the net, become gilled, struggle a few seconds, and then succumb.

The ports in both the stern and bow chambers require periodic cleaning, but, in general, visibility in near-surface waters during the day is limited only by water clarity and the endurance and will of the observer. When the ship is heading into moderate to rough seas, the bow chamber often rises above the surface, causing discomfort to all but the most hardy.

Use of the stern and bow chambers in the *Gilbert* does have limitations. Tunas cannot be observed at night, and they cannot be observed at depths greater than about 25 m. Tunas cannot be followed, because their maneuverability is greater than that of the ship. Several methods were considered to overcome these problems.

Underwater television was tested in 1959 (Strasburg and Yuen, 1960b). A closed-circuit set was installed on the *Gilbert*. A television camera was set in the stern chamber, and another was suspended in the water. Observations of tuna behavior with television were found to be inferior to observations with the human eye under good light conditions. Under poor light, television provided good observations owing to better contrast. The major difficulty with this method was our inability to shift quickly the field of view. The use of television therefore was abandoned.

In 1959, responses to inquiries sent to manufacturers of submersible vehicles indicated that a submarine for studying various biological and oceanographic problems in addition to tuna behavior appeared practicable. Much thought and effort were put forth in the early 1960s on the uses, on the scientific and operational requirements, and on the design of a research submarine. In 1964, an industrial company was contracted by HL to undertake a feasibility and conceptual-design study. The vessel was required to travel as fast as 20 knots while submerged, remain submerged for as long as 6 weeks, dive as deep as 300 m, and have an operational range of 40,000 km. The specified requirements and design of the research submarine (Fig. 5),

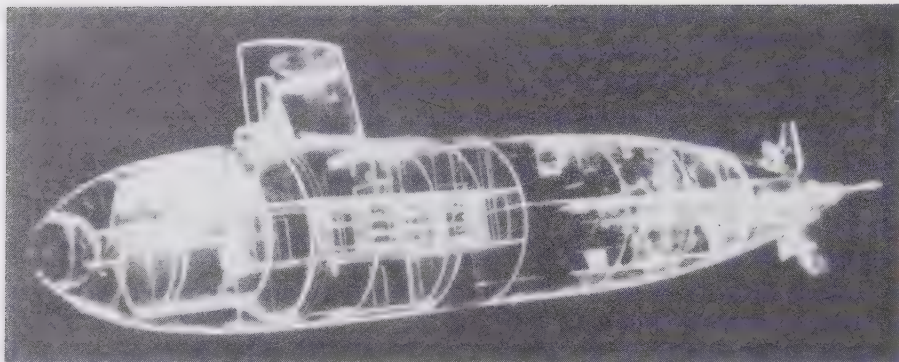


Fig. 5. Plastic model of a proposed nuclear research submarine.

which called for nuclear power, were found to be feasible. One of the great advantages of a submarine is its independence of weather and sea state. Observations are possible in relative comfort while the submarine is submerged despite inclement weather or rough seas. Uses, design, requirements, and facilities of the submarine were presented by Strasburg (1965).

In 1965, HL chartered the *Asherah* (Fig. 6), a submersible about 5 m long, to gain experience in operating and conducting missions with an under water craft. The *Asherah* carried one observer in addition to the pilot. It was operated in the lee of the island of Oahu, Hawaii. Skipjack tuna and kawakawa (*Euthynnus affinis*) were seen on six of the 50 dives with the *Asherah* at depths as great as 152 m (Strasburg, 1966; Strasburg *et al.*, 1968). The tunas were observed preying upon forage fish, but because of the limited speed and maneuverability of the *Asherah* the tunas could not be followed.

A charter of a larger submarine to gain further experience was planned, but owing to insufficient funds the plan was cancelled. Early in 1967, plans for constructing the nuclear research submarine were shelved for the same reason.

Acoustic means of studying tuna behavior at sea were also considered. Acoustic devices could be used to locate and track tunas at night as well as during the day and at depths and distances beyond visual range. Echo-sounders had been used to study movements and speeds of large, deep-swimming tunas (several species of *Thunnus*) by Nishimura (1963, 1966), but for faster-swimming tunas in waters near the surface conventional sonars which transmit sound impulses at fixed intervals and at fixed frequencies were inadequate for tracking. Such fast-swimming fishes could easily escape detection between transmissions. A sonar that could keep tunas under continuous surveillance was desired.

A CTFM (continuous-transmission, frequency-modulated) sonar (Fig. 7) was installed in HL's research ship *Townsend Cromwell* in 1966. Additional equipment has been installed so that pertinent data can be recorded



Fig. 6. The submarine *Asherah*. (a) Loading for transport. (b) Boarding at sea.

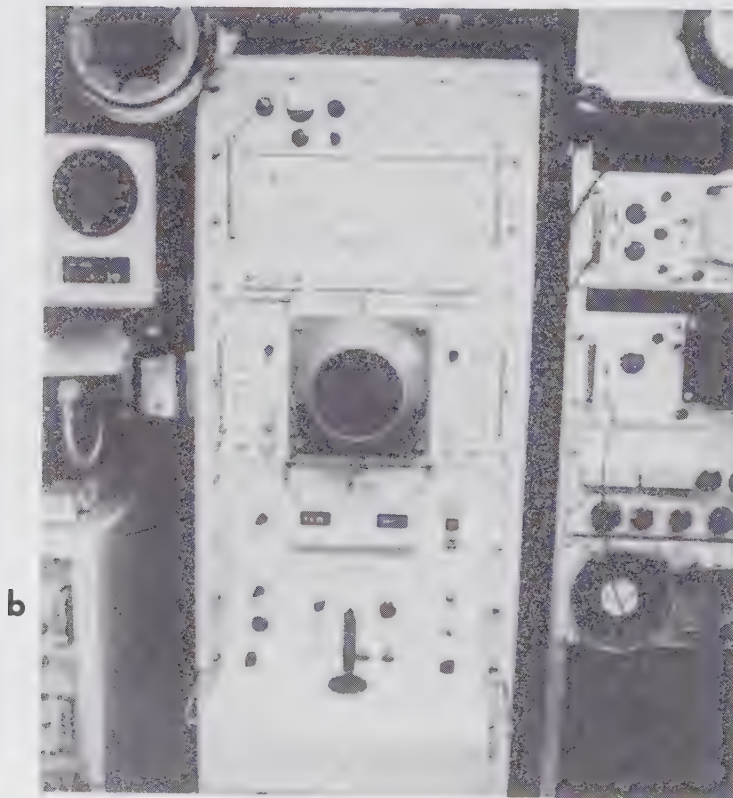
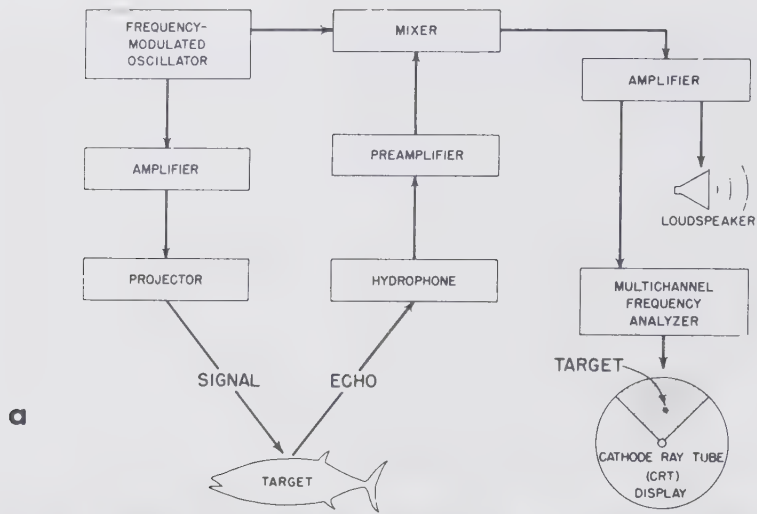


Fig. 7. The CTFM sonar. (a) Block diagram. (b) Control and display panels.

on a 14-channel magnetic tape recorder. The sonar has two operational modes: a search mode with frequencies modulated from 52 to 32 kHz for targets up to 1600 m, and a classify mode with frequencies modulated from 290 to 260 kHz for high resolution at short ranges (100 m). The data from the CTFM sonar are recorded in analog form on magnetic tapes. The tapes are brought ashore, where the data are digitized and then analyzed with the aid of computers. Descriptions of the sonar units and of the operations have been given by Yuen (1967, 1968).

The CTFM sonar, which projects and receives acoustic energy continuously, thereby lessening the possibility of losing a fast-moving target, has been used to observe movements of tuna schools. Diving and swimming behavior of yellowfin and skipjack tunas in relation to their size and to temperatures and depths have been investigated (Yuen, 1968). Schools of skipjack tuna have been followed for many hours continuously while observing their behavior in relation to time and space. These and other studies, including use of ultrasonic tags with the sonar, are in progress.

Hester (1969) attempted to use a CTFM sonar to identify tunas and other species and to determine their sizes by analyzing shifts in frequencies (Doppler shifts) caused by motions of the fishes. The loss of echo strength when fish turned toward or away from the sonar made this method impractical.

Another method used in 1967 for underwater observations was a sea sled towed by the *Gilbert* (Anonymous, 1967). The sea sled was manned by



Fig. 8. Photographing from sea sled.

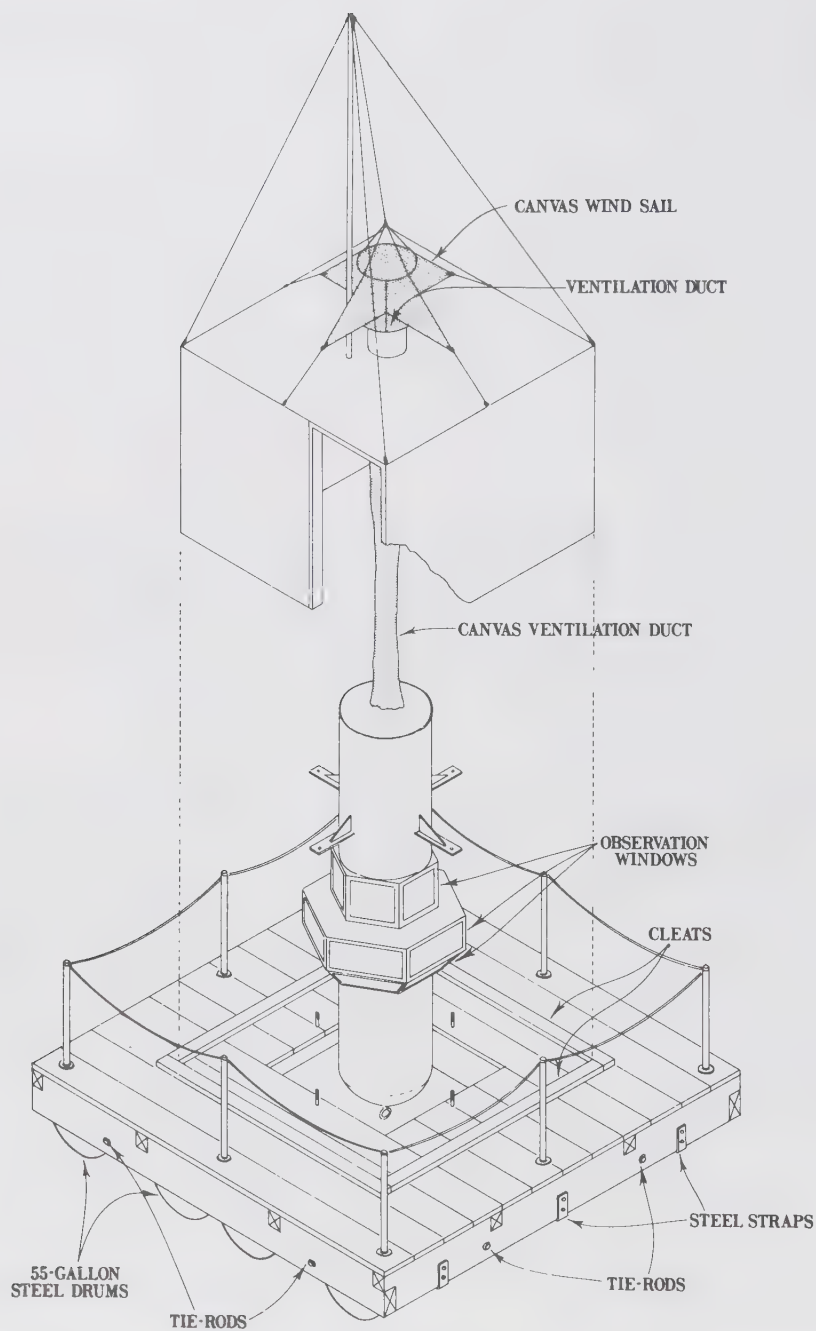


Fig. 9. The raft *Nenue*. (a) Diagram.

two divers equipped with aqualungs (Fig. 8). Communication with the ship was conducted by prearranged signals through a buzzer system. The sled was constructed at the Bureau of Commercial Fisheries Exploratory Fishing and Gear Research Base, Seattle, Washington, by fitting diving planes, windshield, and other equipment to a basket litter.

The behavior of baitfish and the behavior of skipjack tuna preying upon the bait were observed and photographed from the sled, which was towed at about 2 knots at distances up to 50 m behind the ship and as deep as 15 m. The sled proved to be impractical, because by the time it was launched and in operation, the tuna school usually had departed. However, the first underwater observations of courting behavior of skipjack tuna were made (Iversen *et al.*, 1970) before use of the sea sled was discontinued.

During the late 1950s and early 1960s, a number of papers appeared describing parasite-picking and cleaning behavior by fishes and crustaceans in reef communities. Members of HL began to wonder if this phenomenon existed in pelagic environments also. Tunas were often found with ectoparasitic copepods. Which organisms, if any, picked parasites off large

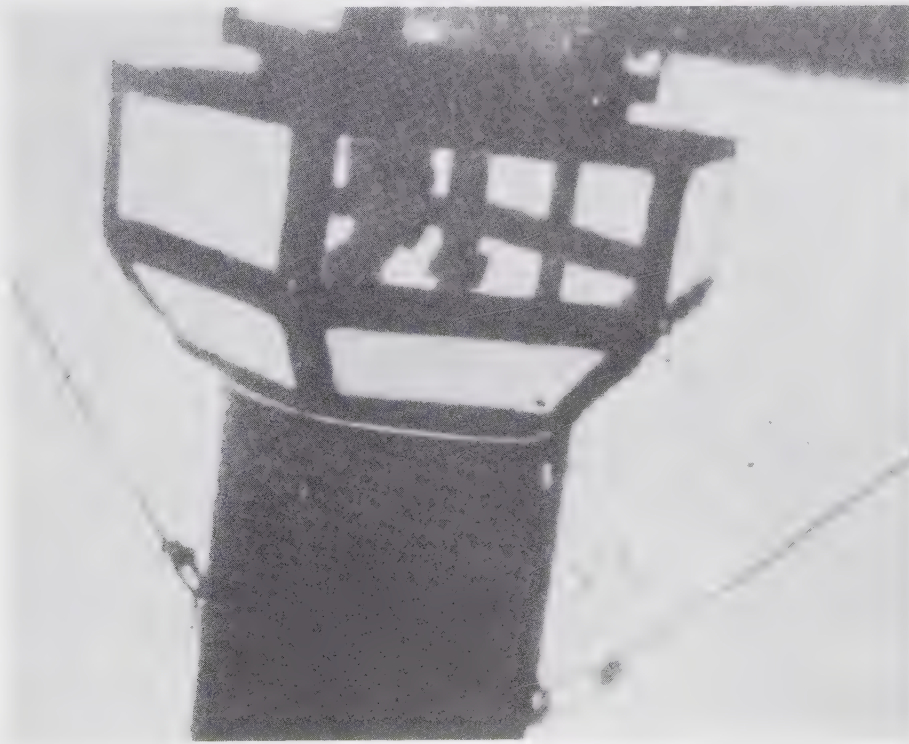


Fig. 9. (b) Observer in cylinder.

pelagic fishes? Tunas were often found in association with drifting objects at sea. These drifting objects almost always had small fishes under them. Could these small fishes act as cleaners for tunas and other pelagic predators?

In an attempt to answer these questions, a raft with observational facilities (Fig. 9) was built in 1962 (Gooding, 1965). The square raft had about 4 m to a side with an aperture in the center through which a steel cylinder was suspended. The cylinder was provided with windows permitting underwater observations in all directions except immediately below. The raft was named *Nenue*, which is the Hawaiian name of *Kyphosus cinerascens*, a fish commonly found under floating objects. The *Nenue* was manned by two persons, who took turns observing in the suspended cylinder. The raft was occupied only during daylight hours. Each evening the observers left the *Nenue* to return to the tending research ship.

The *Nenue* proved to be highly seaworthy, more so than some of the observers. (One observer was removed after 15 min aboard the raft; he had threatened to jump off and swim ashore if he were not taken off.) Many interesting observations and photographs (Fig. 10) were obtained of animals that visited and accumulated under and around the raft. After 13 drifts, 11 in the lee of the island of Hawaii and two south of Hawaii near the Equator, use of the *Nenue* was terminated. Although skipjack and yellowfin tunas were seen, no noteworthy behavior of these tunas was observed (Gooding, 1964; Gooding and Magnuson, 1967). The question concerning cleaning of tunas remains unanswered.

Observations of tunas under floating objects have also been made by Hunter and Mitchell (1967, 1968). They made their observations by diving near floating objects which they found or which they built and placed in the water. Courting behavior and duration of association of black skipjack tuna (*Euthynnus lineatus*) with the floating objects were noted.

III. OBSERVATIONS AND RESEARCH ASHORE

The previously mentioned contract between HL and the University of Hawaii called for determining the reactions of tunas to various chemical, visual, and physical stimuli in the hope that the results might lead to new methods of catching tunas or to improvements in existing methods. To conduct controlled experiments, tunas had to be established and maintained in captivity. Since tunas had never before been held captive for experimental studies, development of methods and techniques for doing so became the first objective.

In 1951, two species of tunas, kawakawa and yellowfin tuna ranging



Fig. 10. Fishes seen from observation cylinder of *Nenue*. (a) Whale shark (*Rhincodon typus*) with unidentified remora. (b) Whitetip shark (*Carcharhinus longimanus*) with pilotfish (*Naucrates ductor*).



Fig- 10 (*continued*). (c) Wahoo (*Acanthocybium solandri*)
(d) Juvenile dolphin (*Coryphaena* sp.)



e



f

Fig. 10 (continued). (e) Freckled driftfish (*Psenes cyanophrys*).
(f) Adult dolphin (*Coryphaena hippurus*).

from 37 to 58 cm long, were successfully established in a small concrete tank and a large pond after initial failure in a small pond (Tester, 1952). Tunas were caught by surface trolling. They were transported to shore in the baitwell of the boat. A dip net was used to transfer fish from the baitwell to the pond or tank.

The concrete tank was about 11 m long, 3 m wide, and 1.2 m deep. Salt water was supplied by pumping from a channel. Baffles had been used to round the corners, because the tunas tended to swim along the walls of the tank and had difficulty in turning, especially if they were swimming rapidly when they reached a right-angle corner. The baffles eliminated the sharp corners. (The corners in the baitwell of the boat also were rounded with baffles.)

The pond had concrete walls built along a channel dredged out of a coral reef. The length was about 115 m, the width about 21 m. The depth of the pond varied from less than 1 m to about 4 m. Salt water was circulated by tidal currents through screened gates.

Kawakawa survived in the pond for over 2 years. Yellowfin tuna were kept in captivity for shorter periods. Attempts to establish frigate mackerel (*Auxis thazard*) and skipjack tuna in captivity were unsuccessful. Dolphins were also successfully established in captivity. Only the kawakawa and yellowfin tuna were used in experiments (Tester, 1952, 1959).

Responses of kawakawa and yellowfin tuna to visual, auditory, chemical, and electrical stimuli were observed in the pond and tank. Hsiao (1952) studied responses to white and colored lights at various intensities, and to continuous and interrupted white light. Hsiao and Tester (1955) conducted experiments on responses to moving lures of various colors. Some of their experiments were conducted when food extracts were introduced into the water. Experiments on attraction and repelling of tunas by sounds of various frequencies were conducted by Miyake (1952). He also investigated sound production by tunas. Responses to chemical stimuli were studied by Van Weel (1952) and Tester *et al.* (1954, 1955) by use of food extracts, water in which bait had been living, and assorted organic and inorganic chemicals. Tester *et al.* (1954) made ersatz baits by impregnating gelatin and macaroni with extracts of fish and squid, and tested them on both captive and wild tunas. Responses to electrical stimuli were studied briefly by Miyake and Steiger (1957). All of these experiments were summarized by Tester (1959).

In the late 1950s, facilities for holding and observing tunas ashore were developed at HL to complement the facilities developed to observe tunas at sea. A salt water well was dug in 1958 near the waterfront to get clean sea water—salt water which had undergone natural filtration and thus was relatively free of pollutants and marine organisms. Because the water lacked oxygen, an aerator consisting of layers of perforated trays was built (Stras-

burg, 1964). A circular, plastic-lined swimming pool (Fig. 11) about 7 m in diameter and 1.2 m deep was set up to hold the captive tunas (Nakamura, 1960).

Initial attempts to establish skipjack tuna in the pool failed. The tuna were captured by pole and line after they had been attracted to the ship with live bait. The fish were pulled out of the water, held by the fishermen while being carefully unhooked, and then placed in the baitwell. In port, the tuna were dip-netted, carried to the pool in a net (wet towels and plastic bags containing seawater were also tried), and released. None survived for more than a few hours. To counteract the excited actions exhibited by skipjack tuna, a drug (thorazine) was injected intramuscularly in some immediately after capture to tranquilize them. The additional excitation from handling while the injection was administered probably offset any tranquilizing effect the drug may have had. Again, none survived for longer than a few hours after release in the pool. All of the skipjack tuna incurred contusions, abrasions, loss of mucus, as indicated by discolored areas of the body, and nervous excitation from handling during these procedures. To prevent these effects, a method which eliminated handling was developed in 1959.

An elliptical steel tank 2.4 m long, 1.8 m wide, and 0.6 m deep was built to transport the tunas from sea to shore. When a fish was hooked, the fishermen swung the pole over the tank, quickly lowered the fish into the tank, and slackened the line to permit the fish to shake the barbless

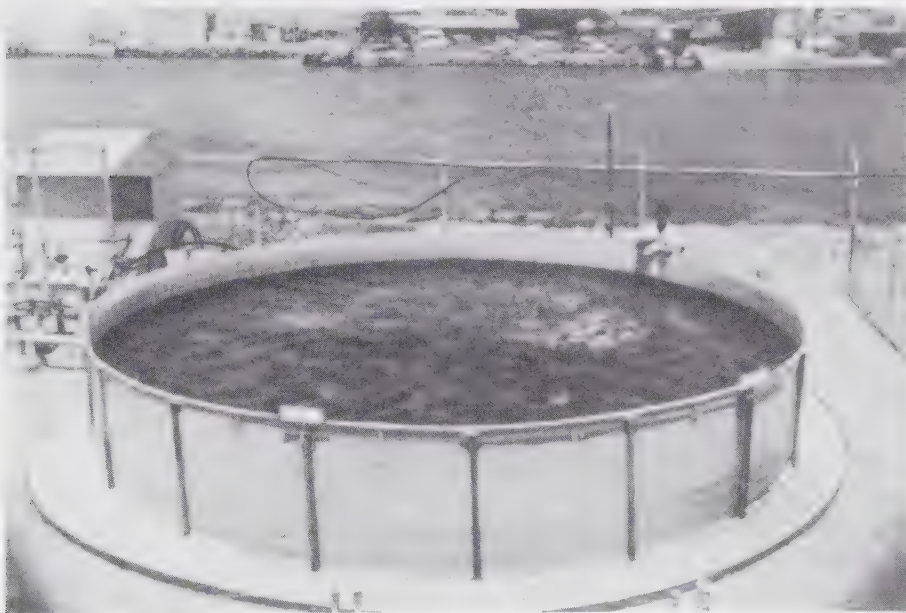


Fig. 11. Circular, plastic-lined swimming pool for holding tunas.

hook out of its mouth. Once inside the tank, which was continuously provided with seawater, the fishes swam along the walls, but since the tank had no corners they were not required to make sharp turns. When the ship returned to shore, the tank was removed with a crane and immersed in the pool, and the fishes were allowed to swim out through a side hatch. Skipjack tuna brought ashore by this method did not have discolored areas, swam less excitedly and more slowly, and were successfully established in captivity. General observations were made on feeding behavior, coloration, swimming and schooling behavior, and recovery from injuries on these captive skipjack tuna (Nakamura, 1962).

After methods and facilities for establishing skipjack tuna and other species in captivity had been developed, additional experimental and observational tanks and pools were built. To determine visual capabilities of tunas, a U-shaped tank 15.9 m long, 4.9 m wide, and 1.2 m deep was built in 1960. The tank (Fig. 12) was enclosed in a Quonset hut to control light. Also, the Quonset hut facilitated observations by preventing rippling of the water surface by winds. Clear glass windows were placed in the ends of the tank. The observer conducted experiments from observation booths placed over the ends of the arms.

Visual acuities of skipjack tuna, kawakawa, and yellowfin tuna were measured in the tank in the Quonset hut. The method involved training tunas to respond differently to horizontal and vertical stripes which were projected onto an opal glass plate at a window in the tank (Nakamura, 1964a, 1968 1969b).

In 1961, a larger well was dug, and a new modified aerator was constructed (Nakamura, 1964b).

Another circular swimming pool was set up in 1962 for conducting experiments on hearing abilities of tunas. The pool was lined with mats made of rubberized pig and horse bristles to provide acoustic insulation. Experiments were conducted from an elevated observation booth built alongside the pool (Fig. 13). Training methods were used again to determine frequencies of sound perceived by yellowfin tuna and kawakawa (Iversen, 1967 1969).

Since the circular swimming pool was found to be most useful for observing tuna behavior, an array of pools was set up in 1962. Six pools were arranged in a ring around an observation tower (Fig. 14). An aerator, which sprayed water through small holes, was built in the center of the observation tower. Water flowed from the aerator into the pools and then out through a drain in the center of each pool. Since seawater from the well was plentiful, recirculation was unnecessary. Windows in the tower permitted views of each tank. Three small huts were constructed, one between each

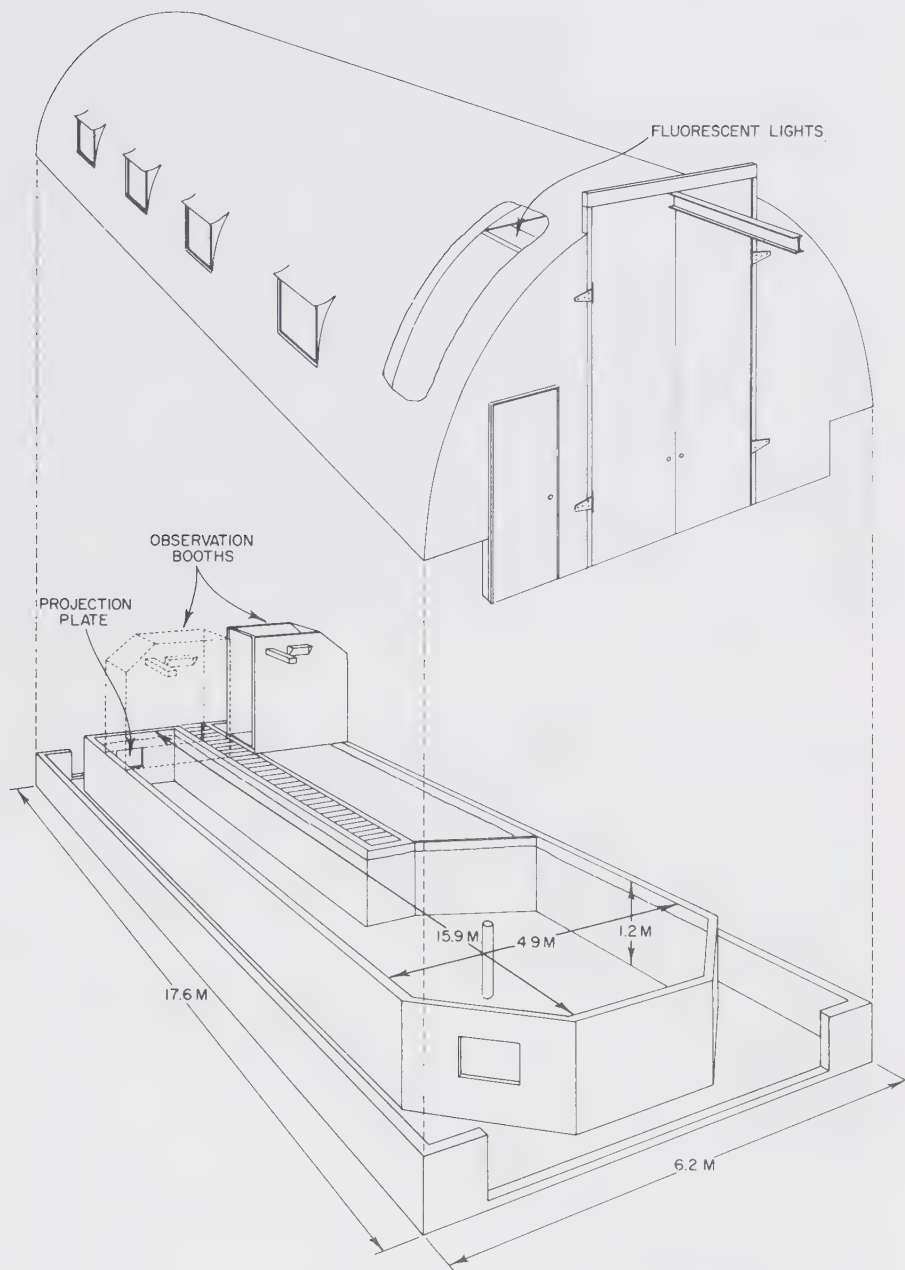


Fig. 12. Diagram of U-shaped tank in Quonset hut.

pair of pools. Windows in the huts permitted observations from below the water surface (Magnuson, 1965).

Awnings were placed over the six-pool complex and the acoustic pool in 1965 to reduce the amount of sunlight entering them. Because a diatom of the genus *Melosira* grew rapidly and profusely in pools open to the sun, the pools had to be cleaned twice a week. After the awnings were placed, the frequency of cleaning was reduced to once every 1 or 2 weeks.

The need to obtain more tunas per trip plus problems concerning the weight and maintenance of the steel transfer tank led to the construction in 1964 of five fiberglass transfer tanks. The new tanks (Fig. 15) were similar to the steel tank in size and design except for removable tops. The fish were released by removing the top and overturning the fiberglass tank in the pool (Nakamura, 1966).

Several species of tunas (Fig. 16) have been kept in our pools at HL. The length of survival has varied with species. Kawakawa have been kept for years, but frigate mackerels (*Auxis thazard* and *A. rochei*) have not survived for longer than a month. Other tunas, such as yellowfin tuna, bigeye tuna (*Thunnus obesus*), and skipjack tuna, have survived for months—generally until they were either sacrificed for experimental reasons, lost owing to accidents, or poached (one of the few people ever to catch tunas by

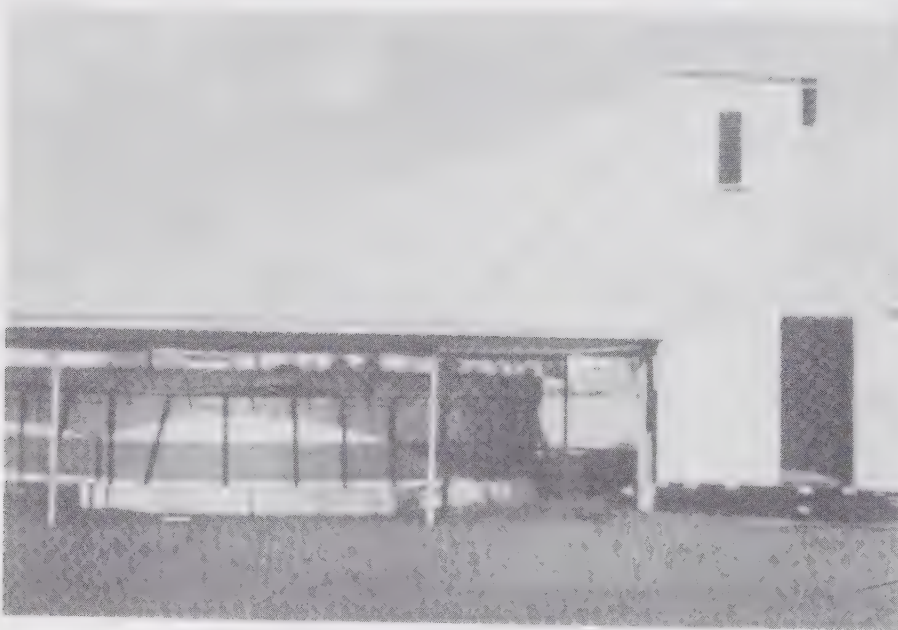


Fig. 13. Pool and observation tower for acoustic experiments.



Fig. 14. Array of six swimming pools around an observation tower with small observation huts between each pair of pools.

spearfishing was a youngster who sneaked into our pools in the evenings). Skipjack tuna, however, have not survived longer than 6 months. Other pelagic fishes, such as the dolphin and the rainbow runner (*Elagatis bipinnulatus*), have also been successfully established in our pools.

Small specimens are sought in fishing for tunas to establish in captivity. The size of the transfer tanks and the pools has favored smaller fish. Also, more small tunas can be placed in a transfer tank and in a swimming pool.

Behavior of tunas in HL's pools has been observed visually from the central observation tower, from the small hut adjacent to the pools (Magnuson, 1965), and from the pool's edge. Cine and still photography and other special equipment have been used in experiments conducted in these pools. High-speed cinematography was used by Walters (1966) to investigate the mechanics of feeding by kawakawa. Schooling behavior of kawakawa has been observed by Cahn (1967). Magnuson (1964*a*, 1966*a,b*, 1969*b*) has studied swimming behavior of kawakawa in relation to respiration and feeding and to hydrostatic equilibrium, and Magnuson (1970) has analyzed the hydrostatic functions of the appendages of kawakawa. He has also determined digestion rates in skipjack tuna (Magnuson, 1969*a*). Changes in color and in body markings have been noted in several species

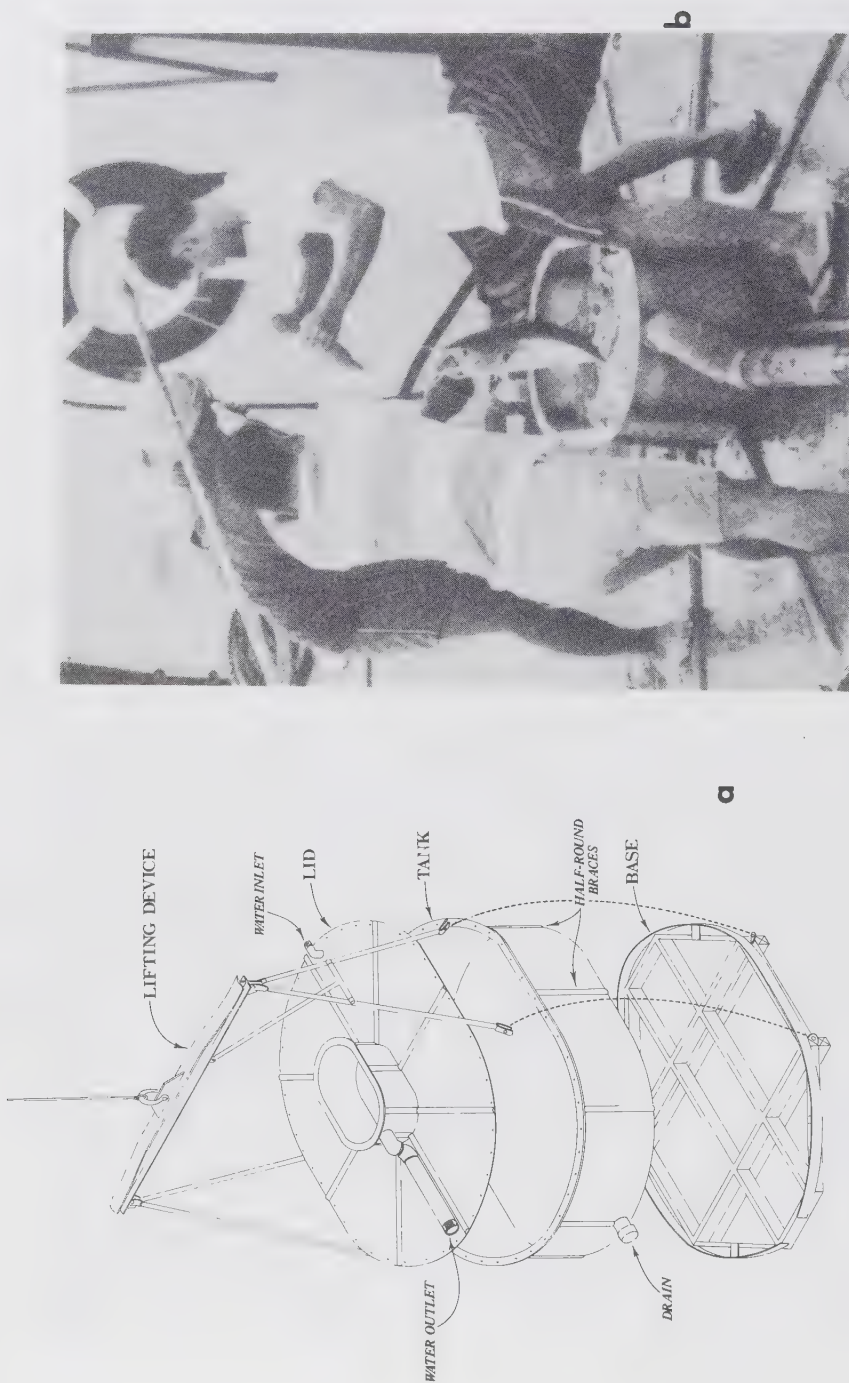


Fig. 15. Fiberglass transfer tank. (a) Diagram. (b) Placing skipjack tuna (*Katsuwonus pelamis*) into transfer tank.



a



b

Fig. 16. Tunas kept in captivity. (a) Skipjack tuna (*Katsuwonus pelamis*).
(b) Bigeye tuna (*Thunnus obesus*).



Fig. 16 (continued). (c) Kawakawa (*Euthynnus affinis*). (d) Kawakawa preying upon a school of baitfish (*Stolephorus purpureus*).

of tunas (Nakamura, 1962; Nakamura and Magnuson, 1965) and also in the dolphin (Murchison and Magnuson, 1966). Some preliminary experiments (unpublished) on olfaction and oxygen tolerance in tunas have been conducted in the pools and have indicated sensitivities and awareness by tunas to dilute concentrations of aquatic odors and to changes in oxygen tension.

While the behavior of captive tunas was observed, questions of sensory capabilities arose which led to studies of the morphology and histology of several organs. The ability of tunas to perceive objects thrown to them before the objects hit the water, even when the surface was rippled, led to examination of the gross morphology and retinal histology of the eyes of several species of tunas (Matthews, unpublished work cited by Tester, 1959). The nature of the small openings of the anterior nares and slitlike posterior nares led to studies of the mechanics of water flow and the morphology and histology of the olfactory organ of skipjack tuna (Gooding, 1963). Questions concerning the silvery tongue of skipjack tuna led to histological examination for taste buds, which were found. A layer of guanine crystals was responsible for the silvery appearance of the tongue (unpublished).

The availability of live tunas at HL has permitted several investigators to carry out anatomical and physiological studies requiring live or fresh specimens. Physiology of muscles of skipjack tuna has been investigated by several workers (Chung *et al.*, 1967; Rayner and Keenan, 1967; Sather and Rogers, 1967). Anatomical and electrophysiological studies of the nerve in the trunk lateral line of skipjack tuna have been made by J. Suckling (1967) and E. Suckling (1967). Oxygen consumption in muscles of skipjack and bigeye tunas has been investigated by Gordon (1968).

Many skipjack tuna, after a few days in confinement, develop a condition we have termed "puffy snout" (Fig. 17). Tissues of the snout begin to swell and become edematous. The swelling spreads posteriorly until the fish is unable to close its jaws and the tissues around the eyes swell to give the appearance of sunken eyes. If left in this condition, the fish dies.

Puffy snout is believed to result from stress due to confinement in small tanks or pools. When tunas with puffy snout are placed in larger tanks or pools, the swelling recedes. We have had kawakawa which developed severe cases of puffy snout when kept in an annular raceway less than a meter wide. When these kawakawa were transferred to one of the swimming pools, the swelling disappeared within 2 weeks. Puffy snout develops more frequently in skipjack tuna than in other species, so we believe skipjack tuna are less able to adapt to confinement in space as small as our pools. Some skipjack tuna that were transported to Sea Life Park, Makapuu, Hawaii, and established in a large display tank (21.4 m top diameter, 10.7 m bottom

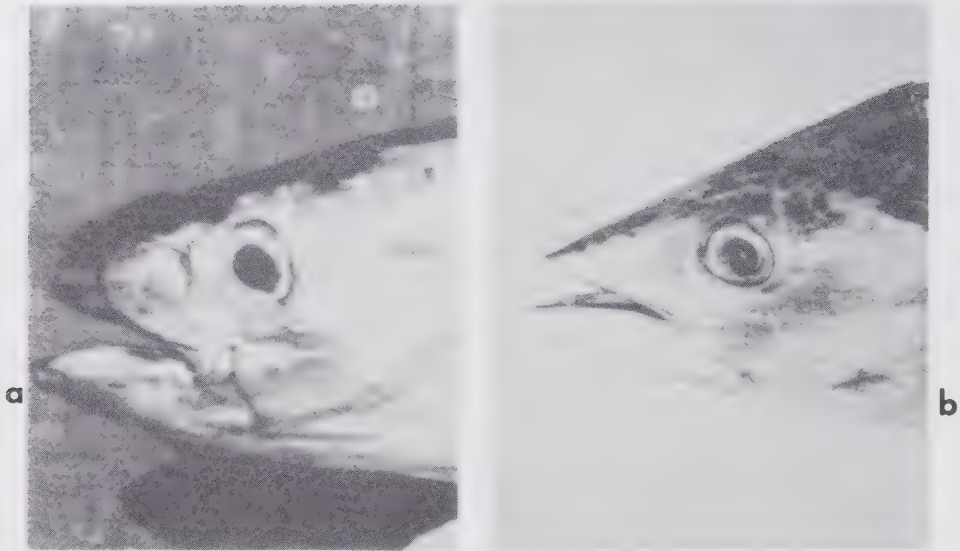


Fig. 17. Head of skipjack tuna (*Katsuwonus pelamis*). (a) Skipjack tuna with puffy snout. (b) Skipjack tuna with normal snout. Pin is stuck in anterior naris.

diameter, 4.3 m deep) did not develop puffy snout. Yellowfin tuna also have developed this malady (Tester, 1952). So have mackerels kept in small tanks. I have seen puffy snout in Pacific mackerel (*Scomber japonicus*) in an aquarium at Scripps Institution of Oceanography, La Jolla, California, and in Atlantic mackerel (*Scomber scombrus*) in an aquarium at The Plymouth Laboratory, Plymouth, England.

Larger tanks undoubtedly are more favorable for maintaining swift pelagic fishes, such as tunas, in captivity. The largest tank in which tunas have been kept in captivity is the tank for public display of fishes at Marine-land of the Pacific, Palos Verdes, California. The tank is about 33 m long, 16.3 m wide, and three stories deep. Pacific bonito (*Sarda chiliensis*) have been maintained in captivity for years. These are the only tuna ever known to spawn in captivity. Courtship, spawning, swimming, feeding, and other activities of this species have been observed in this tank (Magnuson and Prescott, 1966).

In 1965–1966, Inoue *et al.* (1967) attempted to establish tunas in small pools in Japan. A pool, 1.5 m in diameter and 0.6 m deep, was used aboard a vessel at sea. Skipjack tuna died soon after placement in this pool; yellowfin tuna survived for 19 hr. A larger pool, 4 m in diameter and 0.6 m deep, was used ashore. Bonito (*Sarda orientalis*) and kawakawa were kept for over 400 hr. The authors attributed their poor success primarily to insufficient oxygen. In my judgment, the smallness of the pools was also a significant factor.

IV. CONCLUSION

Much has been learned from the use of facilities to observe tuna behavior both at sea and ashore under natural and experimental conditions. Tunas are able to detect dilute concentrations of certain chemicals (Tester *et al.*, 1955; Van Weel, 1952) and to detect sounds of certain frequencies with greatest sensitivity between 300 and 700 Hz (Iversen, 1967, 1969), but vision appears to be the most important sense used in feeding (Hsiao and Tester, 1955; Tester, 1959). Baitfish which are silvery and which are active and which take evasive action when pursued have been observed to elicit greater excitement in tunas, which makes tunas more vulnerable to the pole-and-line fishery; the greater swimming speed and the frequent changes in direction while pursuing the baitfish gives a tuna less time to discriminate between hook and bait. Visual acuity (Nakamura, 1968, 1969*b*) and swimming speed measurements (Walters, 1966; Yuen, 1966) have permitted calculations of distances of visibility of objects and the time tunas have to accept or reject a hook or evade a net (Nakamura, 1969*b*). Color patterns and color changes observed in tunas during their feeding and courtship behavior are probably used as communicating signals between fish and are certainly used by observers as signs that a fish has detected certain stimuli (Nakamura, 1962; Nakamura and Magnuson, 1965). Courtship behavior has been described for three species of tunas (Magnuson and Prescott, 1966; Hunter and Mitchell, 1967; Iversen *et al.*, 1970). Studies on feeding (by skipjack tuna) indicate that indigestible materials pass rapidly ($1\frac{1}{2}$ hr) through the alimentary canal (Nakamura, 1962), that about 15 percent of their body weight is eaten per day, that a full stomach empties in about 12 hr (Magnuson, 1969*a*), and that filter feeding (by kawakawa) is accomplished by swimming over the food rather than sucking it in (Walters, 1966). Studies of schools containing two or more species of tunas have indicated that such schools were formed by separate schools of each species drawn together by a common attractant, such as food (Yuen, 1963). Disruption of schooling orientation occurs during feeding (Nakamura, 1962). The importance of hydrodynamic and hydroacoustic stimuli in augmenting visual stimuli in schooling orientation has been noted (Cahn, 1967). Tunas without gas bladders possess negative buoyancy, and to maintain hydrostatic equilibrium they must swim continuously and use primarily their pectoral fins to obtain hydrodynamic lift (Magnuson, 1969*b*, 1970). These and other results from observations and experiments made with the use of special facilities have significantly advanced our knowledge of tuna behavior. Experience with captive tunas has indicated the ease and rapidity of conditioning them for use in experiments (Iversen, 1967, 1969; Nakamura, 1962, 1968, 1969*b*). However, the results of studies on the responses of captive tunas

to various stimuli have had limited value in predicting the responses of wild tunas to the same stimuli in the open sea (Tester, 1959; Tester *et al.*, 1954).

Development of methods and facilities for studying tuna behavior is continuing. Techniques to anesthetize and revive fast-swimming pelagic fishes without injuries are being developed to permit studies requiring operations on these fishes. Larger pools are planned to maintain larger tunas and skipjack tuna in better health. New techniques and facilities for studies both at sea and ashore will continue to increase our research capabilities and will allow continued growth of our knowledge of tuna behavior.

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Behavioral Thermoregulation by Fishes: A New Experimental Approach

Abstract. Electronic equipment allows fishes, by their spatial movements, to regulate the temperature in experimental tanks. Swimming into warmer water causes the temperature of the entire tank to increase; conversely, swimming into cooler water causes the temperature to decrease. The technique may be adapted for studying simultaneous behavioral regulation of temperature and nonthermal factors.

Fishes, as mobile organisms living in heterothermal environments, can exercise substantial behavioral control over the temperatures they experience. They achieve this by swimming into, or remaining in, areas with certain temperatures and leaving, or avoiding, parts of the habitat with other temperatures.

Understanding how different fishes behave in heterothermal environments is crucial in predicting the ecological

impact of heated effluents. Discharges from the rapidly expanding steam-electric power industry not only heat the receiving waters but do so unevenly, causing strong spatial variation in temperature. Where fishes live in such waters largely determines what metabolic and ecological effects actually accrue.

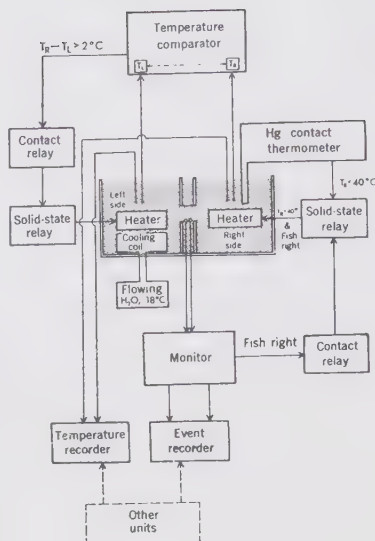
Behavioral thermoregulation by fishes has been investigated primarily through two experimental techniques. The more

Fig. 1. An experimental system for study of behavioral thermoregulation in fishes. The right half of the tank warms at 3° to 5°C an hour (potentially to 40°C) whenever the fish is in the right half and cools at 3° to 5°C an hour whenever the fish is in the left half. The left half of the tank is always 2°C cooler than the right half. Thus, the fish always has available alternative temperatures 2°C apart.

conventional approach is to allow fish to "choose" temperatures by positioning themselves in a horizontal or vertical gradient of temperature (1). The second technique is to permit conditioned fish to control either the upper or the lower limit of temperature by activating a trigger (2); this method, in generalized form, was first applied for studying behavioral thermoregulation in terrestrial vertebrates (3).

Our technique incorporates features of both the earlier methods, but it is unique in several respects. Neither maintenance of temperature gradients in large volumes of water nor elaborate conditioning of experimental subjects is required. Data can be collected continuously and automatically, even in near-darkness; the form of the data is appropriate for direct processing by computer.

A fish can control environmental temperature by dividing his time between the halves of an appropriately equipped aquarium (Fig. 1). The fish is able to



swim from one half to the other by passing through a tunnel in the partition that divides the tank. Passage of the fish is sensed by a pair of photocells in the tunnel; the direction of the passage is determined by the sequence in which the fish interrupts dim beams of light passing across the tunnel from positions opposite the photocells. The signal from the photocells is interpreted by a monitor (based on the bistable multivibrator of computer circuitry), recorded, and used to control heat transfer in the

tank (4). Passage of the fish into one side (say, right) of the tank causes that side to begin warming at 3° to 5°C an hour. The warming of the right side ceases only when the fish swims to the other side; then the right side begins cooling at 3° to 5°C an hour. The temperature of the left side is kept 2°C lower than that of the right side by a comparator-relay circuit. Accordingly, the fish always has available alternative temperatures 2°C apart. Sequential testing and choosing of one temperature over the other results in thermoregulation; thus, the fish serves as its own thermostat.

Young fishes of six species have successfully regulated temperature in the apparatus described above. The record of one specimen of each species is presented in Fig. 2 (5, 6) to exemplify, without typifying, regulatory performances during trials lasting 3 days. Temperatures between 18° and 40°C were potentially available in each case. Sufficient data were collected to demonstrate that regulated temperatures varied significantly among species and were in accord with temperature distributions of the same species in a lake receiving heated effluent (7).

In a subsequent experiment, a naive bluegill (*Lepomis macrochirus*) was required to regulate the temperature of a tank with no differential between halves. The fish maintained a temperature re-

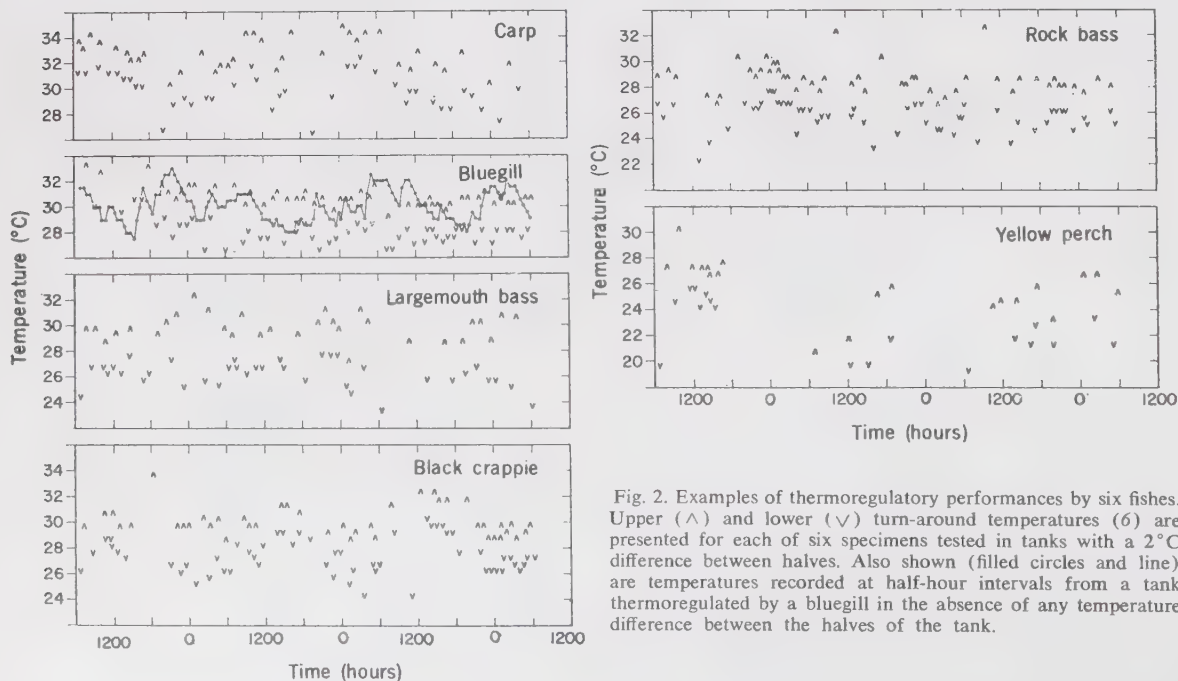


Fig. 2. Examples of thermoregulatory performances by six fishes. Upper (Δ) and lower (∇) turn-around temperatures (6) are presented for each of six specimens tested in tanks with a 2°C difference between halves. Also shown (filled circles and line) are temperatures recorded at half-hour intervals from a tank thermoregulated by a bluegill in the absence of any temperature difference between the halves of the tank.

gime similar to that regulated by other bluegills in tanks with a 2°C difference between sides (Fig. 2). Successful regulation in a tank without a temperature differential indicated that the bluegill learned to associate changes in its spatial position with eventual (but not immediate) changes in temperature.

We believe that our experimental system is amenable to several other modifications that may increase its versatility. If the tunnel is essentially curved on itself to form a doughnut-shaped swimming space, behavioral thermoregulation by continuously swimming fishes of the open sea, such as tunas (8), can be studied. Swimming direction (clockwise, counterclockwise) can control the direction of temperature change; swimming speed can control the rate of temperature change. Thus, fishes could be required to thermoregulate in continuous, gentle (0.1°C per 100 m) gradients of temperature in space that are simulated by changes in temperature through time.

Simultaneous behavioral regulation of temperature and a second, nonthermal factor may be investigated by using a tank with four compartments and two monitors. Concentrations of soluble

substances (such as O_2 , salts, pollutants) can be regulated by a fish-controlled mixing valve; light intensity can be regulated by fish-controlled dimmer circuitry. Movements of the fish in one dimension would regulate temperature and, in the other, the second variable (9). Such an approach would make it possible to measure the joint preference for two independently varying factors.

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4. The circuit diagram of the monitor and other details are available on request from the authors.
5. The specimens 50 to 100 mm long that provided the data for Fig. 2 were taken from waters near Madison, Wisconsin, and were acclimated to 22°C prior to experiments.
6. The upper turn-around temperatures were local temperature maximums recorded from the warmer side of the tank. The i th local maximum, U_i , was the highest temperature recorded along the time sequence such that U_i was separated from adjacent maximums, U_{i-1} and U_{i+1} , by temperatures at least 0.5°C less than $\min(U_{i-1}, U_i)$ and $\min(U_i, U_{i+1})$, respectively. The lower turn-around temperatures were the corresponding local minimums recorded from the cooler side of the tank. The i th local minimum, L_i , was the lowest temperature recorded along the time sequence such that L_i was separated from adjacent minimums, L_{i-1} and L_{i+1} , by temperatures at least 0.5°C greater than $\max(L_{i-1}, L_i)$ and $\max(L_i, L_{i+1})$, respectively.
7. W. H. Neill, thesis, University of Wisconsin (1971).
8. Work proposed by the first two authors and A. Dizon for execution at the Honolulu Laboratory of the Southwest Fisheries Center, National Marine Fisheries Service.
9. Systems analogous to those described here may be used to study behavioral regulation of nonthermal factors at various constant temperatures.
10. Development of the method described here and its initial application were part of a thesis submitted by W.H.N. to the graduate faculty of the University of Wisconsin, Madison, in 1971, in partial fulfillment of the requirements for the Ph.D. degree. The work was done at the Laboratory of Limnology and was supported in part by funds from the Wisconsin Utilities Association and the Office of Water Resources Research, Department of the Interior (MG OWRR B-028-Wis—WRC 70-010M). We gratefully acknowledge the technical assistance of Thomas C. Byles and Bruce K. Quirk.

27 March 1972; revised 3 May 1972

The Interrelation of Biting and Filtering in the Feeding Activity of the Northern Anchovy (*Engraulis mordax*)

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O'CONNELL, C. P. 1972. The interrelation of biting and filtering in the feeding activity of the northern anchovy (*Engraulis mordax*). J. Fish. Res. Bd. Canada 29: 285-293.

A previous study showed that the northern anchovy (*Engraulis mordax*) captures *Artemia* adults (3.7 mm long) by biting and *Artemia* nauplii (0.65 mm long) by filter feeding. This study shows that the ratio of biting to filtering activity in small schools varies with the relative concentration of *Artemia* adults and nauplii in the water. Activity was half biting and half filter feeding when *Artemia* adults were 2% by dry weight of the available biomass, but was entirely biting when *Artemia* adults exceeded about 7% of the biomass.

It is estimated that when feeding activity is half biting and half filtering, *Artemia* adults and nauplii would contribute equal dry weights to ingestion, and that the sum of the two would be the same as that possible if total activity had been filtering. When relative concentration of *Artemia* adults is high enough to induce total biting activity, the dry weight ingested per unit time would be double that possible by filtering alone on the nauplii present.

Ratios of large-to-small crustaceans are relatively high near the surface at night off southern California, which suggests that biting activity could often exceed 50% of total feeding activity. If the plankton does support a high percentage of biting activity, a large part of the area should usually provide the anchovy with its daily nutritional needs.

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Une étude antérieure a démontré que les anchois (*Engraulis mordax*) capturent les *Artemia* adultes (3.7 mm) à coups de dents et qu'elles se nourrissent par filtration de nauplii d'*Artemia* (0.65 mm). La présente étude révèle que le rapport morsure-filtration dans les bancs de taille restreinte varie en fonction de l'abondance relative des *Artemia* adultes et des nauplii dans le milieu. L'alimentation se fait moitié par morsure, moitié par filtration, quand les *Artemia* adultes constituent 2% en poids sec de la biomasse disponible, mais entièrement par morsure quand les *Artemia* adultes dépassent environ 7% de la biomasse.

Nous estimons que lorsque l'alimentation se fait moitié par morsure, moitié par filtration, les quantités d'*Artemia* adultes ingérées sont les mêmes en poids sec que celles des nauplii, et que le total des deux équivaut au total possible par filtration seulement. Lorsque la concentration en *Artemia* est suffisante pour induire une activité entièrement de morsure, le poids sec ingéré par unité de temps serait deux fois plus grand que celui possible par filtration seulement des nauplii.

La proportion des gros crustacés par rapport aux petits est relativement élevée près de la surface, la nuit, au large de la Californie méridionale. La morsure constituerait donc plus de 50% de l'activité alimentaire totale. Si, en réalité, le plancton est l'objet d'un fort pourcentage de morsure, une grande partie de la région pourrait généralement répondre aux besoins alimentaires quotidiens de l'anchois.

Received July 20, 1971

LEONG and O'Connell (1969) showed that the northern anchovy (*Engraulis mordax*) captured *Artemia* nauplii by filtering, but captured the much larger *Artemia* adults individually by directed biting (particulate feeding) when each food was presented separately. Food biomass was accumulated more rapidly

by biting than by filtering. They hypothesized that the anchovy could not sustain its daily food requirement by filtering alone off southern California, except in limited areas of heavy plankton concentration. Their study suggested that the role of biting activity could not be satisfactorily appraised until the response of the fish to mixed size assemblages of food organisms was better understood.

Printed in Canada (J2245)

The ability of the anchovy to capture larger but less abundant organisms by biting in addition to capturing the more numerous small organisms by filtering could be advantageous for two reasons. First, larger crustaceans with good escape responses might avoid capture by filtration. The directed nature of biting probably overcomes the escape response. Second, a greater volume of water can be searched in biting than can be strained in filtering. Either of these factors could raise the average amount of food eaten above what it would be by filtering alone.

The two modes of feeding suggest that the anchovy is a selective feeder. A number of authors have suggested on the basis of field studies that clupeoid fishes feed selectively and that food-organism size is a major determinant. Hiatt (1951), for example, showed that the nehu (*Stolephorus purpureus*) was larger and tended to have more food in its stomach in areas where large crustaceans were more available, and appeared to select these organisms. Brooks and Dodson (1965) concluded that the alewife (*Alosa pseudoharengus*) tended to select the larger crustaceans. Shen (1969) showed that zooplankters were generally more numerous than phytoplankters in the stomachs of *Engraulis japonicus*, and that the larger organisms, up to 5 mm long (Euphausiacea, Ostracoda, *Paracalanus*, and Rotifera), were commonly present in the stomachs, though only occasionally in relatively high abundance. Loukashkin (1970) showed that zooplankters were usually far more abundant than phytoplankters in the stomachs of *E. mordax*, and concluded that large copepods and euphausiids were the most important food items.

These studies imply that larger crustaceans are taken in preference to smaller organisms as their relative abundance permits. They suggest the hypothesis that ingestion rate will vary in respect to biomass concentration of plankton as the proportion of biting to filtering activity varies in some way with the relative abundance of large and small organisms in the concentration. This study attempts to describe the way in which these two kinds of feeding activity are used by small schools of anchovies in the laboratory when they are presented with different density combinations of *Artemia* adults and nauplii. The implications of these results are discussed in relation to anchovy feeding in the sea.

Procedure

Feeding trials were carried out in an arrangement of two plastic pools with connecting trough and gates (Leong and O'Connell 1969). The pools were supplied with a continuous flow of filtered sea water and each contained 3.65 m³ of water at a depth of 0.5 m. The pools were under a 12-hr day–12-hr night cycle of il-

lumination, but all trials were during the day. Temperature ranged from 16 to 19 C.

For each trial, water flow was turned off and 16–20 fish were diverted from a large reserve school in one pool to the trough and then admitted to a prepared food situation in the other pool. Three observers scored feeding activity for a period of 8 min, after which the fish were returned to the reserve school. All trials were preceded by at least 24 hr without feeding and samples from the reserve school always showed empty digestive tracts.

The food situation was established for each trial by placing a known number of *Artemia* adults averaging 3.7 mm long (0.5 mg dry wt) and an approximately known number of *Artemia* nauplii averaging 0.65 mm long (0.00145 mg dry wt) in the experimental pool and dispersing them by stirring gently with wide mesh dipnets. *Artemia* adults were precounted for all but a few high density trials, for which they were estimated by wet weight. Post-trial estimates of nauplii density were made from samples taken from the pool just before the fish were admitted.

The basic units of observation over the 8-min feeding period were 10-sec intervals marked by an audible timing device. Each of the three observers recorded the activity of a single fish as biting (B), filtering (F), or none (0) for successive intervals. The two kinds of activity, which differ by a factor of at least 10 in duration of mouth opening (Leong and O'Connell 1969), were easily distinguished. Instances of one fish displaying both kinds of activity in the same 10-sec interval were rare. Prior to each trial, each observer was assigned a different part of the school — front, middle, or rear — and chose fish in these approximate positions at the start of each interval. Observer differences will be considered in conjunction with the analysis of position differences in activity.

A pilot study indicated that the proportion of biting to filtering activity in the school might vary in relation to the relative concentration of the two sizes of *Artemia* in the water, only when *Artemia* adults were at fractions of less than about 10% of the dry weight of total food concentration. Feeding activity appeared to be directed almost entirely at larger organisms when they constituted greater fractions than this of the available food. Groups of six fish allowed to feed for 5 min averaged 56% of adult *Artemia* in dry weight of digestive tract contents, when these larger organisms were 5% or less by dry weight of the food in the water (four trials), but averaged 95% or more adults in digestive tract contents when adults were between 7 and 99% of the food in the water. The experiment was therefore limited to density combinations in which *Artemia* adults were a small fraction of the total dry weight of available food. The fractions varied from 0.4 to 11% of total dry weight, with over half of the trials having 3% or less and another one-third having between 3 and 7%. The density ranges of each food type were extended as far as practicable within this limitation.

The pilot study also suggested that a behavioral measurement would probably be a more reliable indicator of the response to the food situation existing at the start of each trial than would digestive tract

contents. Though both activities were evident in the trials that showed approximately equal dry weight fractions of the two food types in digestive tracts, and biting was distinctly dominant in the other trials, activity did appear to shift towards less biting and more filtering in the last few minutes in a few cases. Such change probably signified elimination of all or most of the larger organisms as feeding progressed.

Effect of *Artemia* Adult and Nauplii Densities on the Proportion of Biting to Filtering Activity

The response of the school to food concentrations in which *Artemia* adults were a small fraction of total dry weight at the start of the trial is described from the feeding activity occurring in the first 3 min of 46 trials. Though response was measured for 8 min, biting activity tended to be constant and maximal only during the first 3, as indicated by activity averaged for all trials (front bars in Fig. 1). Filtering activity was not maximal in the first 3 min, but rather started low and increased steadily over the feeding period. Schools exposed to nauplii alone (rear bars in Fig. 1) showed the same kind of steady increase in filtering activity.

Though interpretation of the first minute is uncertain, the response patterns in general suggest that where *Artemia* adults are present along with nauplii, biting tends to replace filtering rather than be in addition to it.

Figures 2 and 3 show the relation of biting and filtering activity in the first 3 min of feeding to the starting densities of *Artemia* adults and nauplii. Biting tended to increase with adult density and filtering tended to increase with nauplii density, but in each case the relation of response to density appeared to be lower where densities of the alternative food

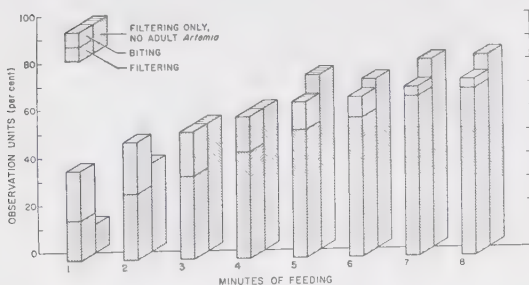


FIG. 1. Percentages of filtering and biting activity for each minute of the trial period. Front bars represent averages by minute for 42 trials in which fish were exposed to combinations of *Artemia* adults and nauplii. Rear bars represent averages by minute for 6 trials in which fish were exposed to nauplii alone. Average nauplii density was higher for the latter series of trials.

were higher. This suggests that the school shows a ratio of biting to filtering activity that varies with the densities of both groups of *Artemia*.

Table 1 indicates the effect of each type of food on the relative amounts of biting and filtering, which was calculated as percent biting (the ratio of 10-second time units scored as biting to the total scored as biting and filtering in the first 3 min). The table is based on the 24 trials with *Artemia* adults between 4 and 50/m³ and *Artemia* nauplii between 100,000 and 500,000/m³. The distribution of these trials permitted separation into four equal groups representing low and high density treatments of comparable range for each food factor. The food density means and ranges are given along with the average percent biting response for each of the food treatment combinations. Percent biting increased with *Artemia* adult density at both levels of nauplii density and decreased

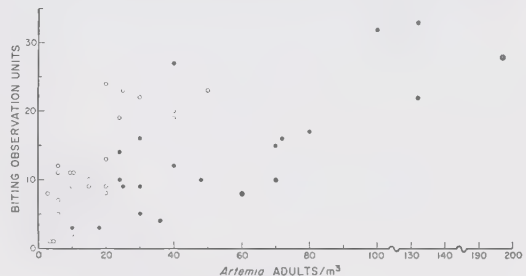


FIG. 2. The relation of biting observations to density of *Artemia* adults for 46 trials in which both adults and nauplii were present. Density of *Artemia* nauplii: O, < 400,000/m³; ●, > 400,000/m³.

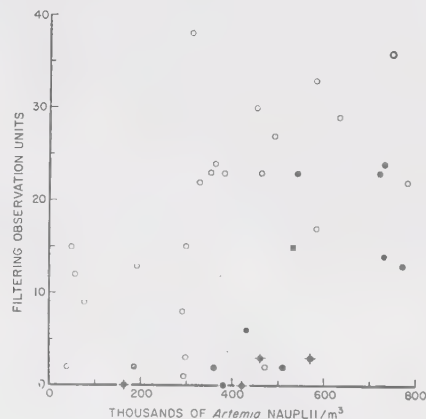


FIG. 3. The relation of filtering observations to density of *Artemia* nauplii for 46 trials in which both adults and nauplii were present. Density of *Artemia* adults: O, < 40/m³; ●, > 40/m³; ◆, > 100/m³.

with nauplii density at both levels of adult density. An analysis of variance showed that only the two main effects were important, and that percent biting was largely associated with the density of *Artemia* adults ($F = 11.0$, $df\ 1/20$), but nauplii did have a discernible effect ($F = 1.58$, $df\ 1/20$), which would probably have been stronger if the average density of *Artemia* adults had been more nearly alike for the two treatment combinations in which adults were high. In any event, percent biting will be described as a function of *Artemia* adult density for broad ranges of nauplii density.

Trends of relative biting and filtering are shown by normal probability plots of percent biting (PB) on *Artemia* adult density for three different ranges of nauplii density (Fig. 4). Probit analysis was used to estimate the parameters of the fitted lines for suitably limited ranges, i.e., for values excluding 0 and 100% response. Individual points represent PB values for trials pooled in successive intervals of four *Artemia* adults/m³. Trials with nauplii densities below 100,000/m³ were excluded because they encompassed too narrow a range of *Artemia* adult density,

and trials with adult densities above 100/m³ were excluded because a few would have produced responses of 100%, a nonexistent value on the probit scale.

The data for the highest range of nauplii density were judged to be inconclusive because the PB values obviously did not show a significant trend. The only distinguishable increase in response was the PB value for the highest *Artemia* adult density. The arrays for the other two ranges, however, do show good evidence of linear trends, and regressions for each can therefore be taken to represent cumulative normal distributions (Bliss 1967) with parameters $\hat{\mu}$ and $\hat{\sigma}$, where $\hat{\mu}$ is the mean density of adults at 50% response and $\hat{\sigma}$ is the standard deviation. Values for these parameters are given in Table 2. The χ^2 values show that the array of PB values for the lowest

TABLE 1. Average percent biting for four treatment combinations of *Artemia* adult and nauplii density. Mean density and range of adults (A) and thousands of nauplii (N) is shown for each treatment combination.

<i>Artemia</i> adult density	<i>Artemia</i> nauplii density	
	Low	High
Low	42	24
	A 10(4-15) N 242(107-311)	11(6-18) 389(325-465)
High	79	69
	A 27(20-40) N 219(141-298)	35(20-50) 416(360-484)

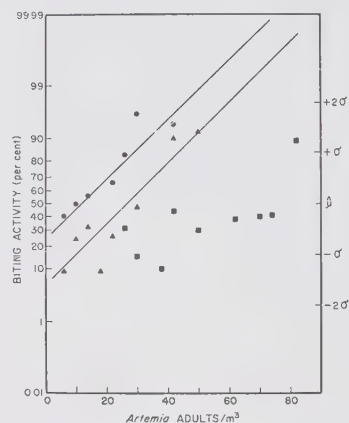


FIG. 4. Probit regressions of percent biting response on density of *Artemia* adults for three categories of *Artemia* nauplii density. *Artemia* nauplii density: ●, 100-300 thousand/m³; ▲, 300-500 thousand/m³; ■, > 500 thousand/m³. Mean and standard deviation of response are indicated at right.

TABLE 2. The normal cumulative distributions that describe the relation of percentage biting response to density of *Artemia* adults for three categories of *Artemia* nauplii density. $\hat{\mu}$ is mean and $\hat{\sigma}$ is standard deviation of the distributions. n is the number of 10-sec response units and N is the number of *Artemia* adult density classes in which they occurred. Significant χ^2 values indicate departure from normality.

Nauplii density range '000/m ³	n	N	$\hat{\mu}$	$\hat{\sigma}$	χ^2
100-300	214	7	11.78±2.78	17.10±3.44	4.08
300-500	342	8	26.70±1.34	17.00±1.76	16.21 ^a
500 ⁺	381	9	—	—	27.58 ^b

^a $P = 0.05$.

^b $P = 0.01$.

range of nauplii density is acceptably normal, while that for the high range is not, and that for the middle range is uncertain. In view of the graphic evidence, the deviation from normality indicated for the middle range is probably attributable to inflation of variability, a not unexpected result where the experiment occurred over a long time and the results from individual trials were combined irrespective of the time element for analysis. Use of the uncorrected estimates of $\hat{\mu}$ and $\hat{\sigma}$ means only that the standard errors for each should be considered conservative.

The regression lines for the low and middle ranges of nauplii density, which have the same slope (0.59), and which represent normal cumulative functions that differ only in mean ($\hat{\mu}$), show that the proportion of feeding activity devoted to biting rather than filtering by small schools of anchovies increased as density of *Artemia* adults increased, and/or as density of nauplii decreased. The expected percent of biting activity can be estimated directly from Fig. 4 for any density of *Artemia* adults with *Artemia* nauplii assumed to be at a density of 200,000/m³ or 400,000/m³.

The above distributions define percent biting as an average for the school, but the average is based on summation over three positions in the school, and analysis by position indicates that there is a gradation of feeding response within the school. To evaluate the significance of position differences, however, it is necessary to test the hypothesis that variation in feeding activity with position is not associated with variation between observers. Since the positions

were not occupied an equal number of times by each observer among all trials, the hypothesis was tested for 24 trials in which each observer was at each position eight times. The numbers of 10-sec intervals scored as biting (B), filtering (F), and zero (0) activity over the first 3 min is shown in Table 3 by position for all of these trials, and by observer for each position. Feeding activity differs markedly between positions ($\chi^2 = 74.6$), with biting higher than filtering at the front and filtering higher than biting at the middle and rear. Though not grouped as such in the table, differences between position for each observer show the same marked pattern. χ^2 values are 43, 44, and 52 (df = 4) for observers A, B, and C, respectively.

The χ^2 values for the three positions, as given in the table, show, on the other hand, that all three observers scored essentially the same distribution of biting, filtering, and zero observations for the front and rear positions. There is significant deviation from expected at the middle position, although all three observers did score more filtering than biting. Inequities in the average food situation represented by the eight trials for each observer were greater at the middle than at the front and rear positions, and may have been partly responsible for the higher deviations in this set. Variation at the middle position notwithstanding, it can be concluded from these tests that differences between positions are far greater than differences between observers.

The nature of the gradient in feeding activity is evident in probit regressions for each of the three school positions—front, middle, and rear—for

TABLE 3. Contingency tables and χ^2 values for relation of the number of 10-sec intervals scored as biting (B), filtering (F), and zero (0) feeding activity in 3 min to position of observation in the school, and to observer at each position. n = number of feeding trials in which each position was observed. df = degrees of freedom. Expected distributions are shown in parentheses.

Position	Observer	n	B	F	0	χ^2	df
Front	All	24	132	51	249	74.6***	4
Middle	All	24	59	174	199		
Rear	All	24	74	137	221		
			(88.3)	(120.7)	(223.0)		
Front	A	8	51	19	74	8.32	4
	B	8	42	10	92		
	C	8	39	22	83		
			(44.0)	(17.0)	(83.0)		
Middle	A	8	29	56	59	19.3***	4
	B	8	18	45	81		
	C	8	12	73	59		
			(19.7)	(58.0)	(66.3)		
Rear	A	8	28	50	66	7.14	4
	B	8	20	52	72		
	C	8	26	35	83		
			(24.7)	(45.7)	(73.7)		

trials in the 100,000–300,000 nauplii/m³ range (Fig. 5A) and for trials in the 300,000–500,000 nauplii/m³ range (Fig. 5B). The regressions were fitted to PB values calculated for each position for the same combinations of *Artemia* adult and nauplii densities for which the average PB values were calculated. For the lower nauplii range (Fig. 5A) no regression was calculated for the front position because five of the PB values were 100%. These and the two values shown for the front position, nevertheless, demonstrate that fish in the lead position consistently showed far higher percentages of biting than fish in following positions. For the higher range of nauplii density (Fig. 5B) the same phenomenon is evident but less pronounced. Here, however, the line for the middle position indicates that percent biting response became as strong in the middle as in the front position when *Artemia* adult density was high. The general pattern is clearly a gradation from higher percent biting at the front to lower percent biting at the rear with variations in the strength and intensity of gradient dependent on the relative abundance of the two sizes of organism in the water.

Contributions of Biting and Filtering to Ingestion Rate

Average ingestion rate for individuals in the school, and the contribution of *Artemia* adults and nauplii to this average, must depend on the rates at

which the two sizes of organism are captured as well as on the ratios for the two associated feeding activities in the school. The relation of numbers captured to density for nauplii is suggested by equation 5 in Leong and O'Connell (1969). Those authors also described feeding rate for *Artemia* adults, but only for densities above 1000/m³. Feeding rate for low densities of adults can be estimated for simulated daylight conditions from the pilot study described under methods above. In 10 of the trials nauplii were essentially ignored by the fish, and the relation between *Artemia* adults in the water and in digestive tracts was

No./m ³	6	6	8	8	12	18	100	100	1000	10,000
No./fish	1	1.5	2	3	4.7	8.3	19	25	95	78

The correlation is obvious, except that average number consumed was no higher for a density of 10,000/m³ than for a density of 1000/m³. This is consistent with the finding by Leong and O'Connell (1969) that number of *Artemia* adults consumed by the anchovy was not related to density over the range 1000/m³–25,000/m³. If the 10,000/m³ entry is excluded on the assumption that it is far above some inflexion point where feeding rate ceases to increase with density, the relation for the remaining nine pairs of values ($r = 0.97$) is described by the line

$$\text{Log } N = 0.82 \text{ Log } D - 0.36 \quad (1)$$

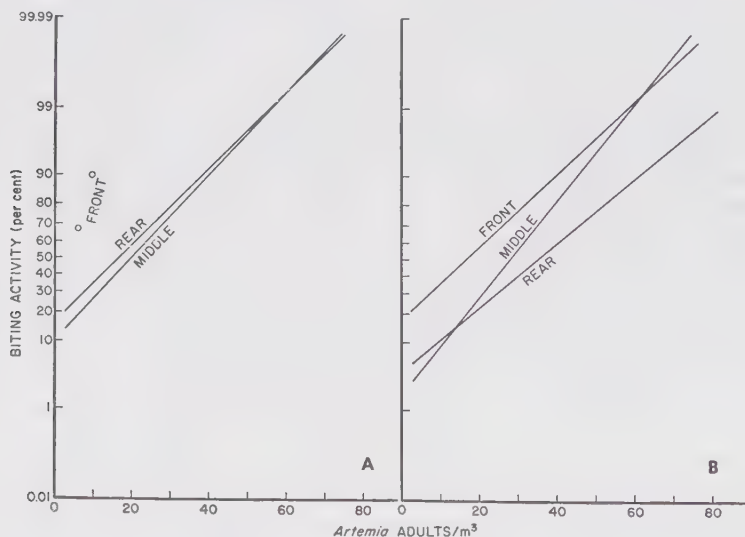


FIG. 5. Probit regressions of percent biting response on density of *Artemia* adults for front, middle, and rear positions in the school for trials with A, *Artemia* nauplii in the 100–300 thousand/m³ range, (No regression line is shown for the front position because 5 of the 7 points were off scale at 100%), and B, *Artemia* nauplii in the 300–500 thousand/m³ range.

where N = average number of *Artemia* adults consumed in 5 min, and D = average number of *Artemia* adults/m³ present in the water at the start of feeding.

Under the assumption that basic rates derived from equation 1 above and equation 5 in Leong and O'Connell (1969) are effective in proportion to the ratios for the two kinds of feeding activity in the school, the products of these basic rates and ratio values for the densities present should provide a partial rate for each size of organism. The sum of the partial rates, expressed in comparable units, will be the average total rate for the density combination. Basic, partial, and total rates are shown for four density combinations in Table 4. The rates are expressed as the milligram dry weight that would be consumed in 1 min by a fish weighing 5 g (average weight of fish in pilot study). The four density combinations are based on the midpoints of the nauplii density ranges for which probit regressions were calculated and on the adult densities indicated by those regressions (Fig. 4) for 50 and 99% biting activity.

The values in Table 4 indicate that when dry weight concentration of *Artemia* adults in the water is 2% of the total concentration, the basic rates are similar for the two sizes of organism and particulate and filter feeding activity are equal. Under these circumstances the ingestion rate for both sizes together, or total rate, is no greater than would be possible by filtration alone on the nauplii. However, when the dry weight concentration of *Artemia* adults is in the order of 5.5–8% of the dry weight of adults and nauplii together, the basic rate for *Artemia* adults is approximately double that for nauplii. Under these circumstances total ingestion rate is approximately double that possible by filtration alone, and filter feeding contributes little to total ingestion.

The possibilities of ingestion rate, of course, are not limited to the combinations illustrated. Total ingestion rate would presumably be intermediate between those for 50 and 99% biting activity if density of larger organisms were intermediate between those that support such levels of biting. Ingestion rate might also be more than double the filtration potential if the density of larger organisms were markedly greater than necessary for the 99% level of biting activity. Also, ingestion rates might be somewhat lower, or the concentrations of large organisms necessary to sustain them somewhat higher than indicated, if escapement of larger crustaceans in the sea is appreciable. Though biting may tend to counteract escapement, the calculations are based on *Artemia* adults, which appear to have no effective escape response.

Interrelation of Biting and Filtering in the Sea

Although the anchovy probably relies on filter feeding for a steady supply of food in the sea, this supply may often fail to sustain the daily nutritional requirement, as already hypothesized. The experiments described here suggest that biting could be an augmenting activity of some consequence, depending on the size composition of the plankton. O'Connell (1971) showed that plankton pump samples from surface waters off southern California vary greatly in relative abundance of large and small crustaceans. Of the constituents described, small copepods, with an average dry weight equivalent of 0.0025 mg, and euphausiids, with average dry weight equivalents of 0.042 mg for day samples and 0.293 mg for night samples, most closely approximate the *Artemia* nauplii and adults used in the laboratory

TABLE 4. Estimated ingestion rates for density combinations of *Artemia* adults and nauplii at which biting activity is 50 and 99% of total feeding activity.

Percent biting activity Organism type	Low nauplii density				High nauplii density			
	50		99		50		99	
	Nauplii	Adults	Nauplii	Adults	Nauplii	Adults	Nauplii	Adult
Density no./m ³	200,000	12	200,000	52	400,000	27	400,000	66
Dry wt mg/m ³	290	6	290	26	580	13.5	580	33
Adult % of total dry wt		2.0		8.2		2.3		5.4
<i>Ingestion rates (mg dry wt/min) for above densities</i>								
Basic	0.49	0.34	0.49	1.1	0.73	0.65	0.73	1.4
Partial	0.24	0.17	0.01	1.1	0.37	0.33	0.01	1.4
Total		0.41		1.1		0.70		1.4

study. They also constituted the bulk of the dry weight of the samples. Averages for five cruises indicated that euphausiids were 3–5% of the dry weight of both groups during the day and 21–66% at night. These percentages suggest that anchovy feeding in surface waters would be chiefly filtering in the daytime and chiefly biting at night, with ingestion rate far exceeding the filtration potential in the latter period.

However, the small laboratory school can scarcely represent more than the leading edge of many schools in the sea. Since percentage of biting diminished noticeably in following positions in a small school, it is possible that diminution extends to a complete lack of opportunity for biting activity for most of the fish in large, compact schools. This would result in a lower capture rate of the larger crustaceans and a lesser elevation of total digestion rate, on the average, than might be expected for a small school exposed to the same relative concentrations.

There is circumstantial evidence to suggest, on the other hand, that the anchovy schools more loosely when larger food organisms are abundantly available. In the laboratory experiments the fish schooled under all trial circumstances, but in the presence of the higher densities of *Artemia* adults, where initial activity was largely biting, they appeared to swim faster and be more widely separated than in circumstances where most of the activity was filtering. Hobson (1968), on the basis of extensive field observations, found that the flatiron herring, *Harengula thrissina*, remained inshore in dense schools during the day and moved offshore, possibly in looser aggregations, to feed at night when shrimp-like crustaceans were most abundant in midwaters. He cited other clupeids that have been observed to break up into smaller, more loosely associated feed-

ing groups at night. Such a behavior pattern, which might well apply to the northern anchovy, would operate to improve the average rate of encounter with larger crustaceans, and thereby raise the average rate of ingestion in respect to the filtration potential, although perhaps still not as much as might be expected for a small laboratory school.

Whatever the daily feeding cycle of the anchovy, it appears that opportunities for biting activity would be greatest in dim light — either at depth during the day, or near the surface at night. Because of strong vertical migration, high densities of euphausiids are common only under these conditions, and O'Connell (1971) has shown that the larger copepods, which may also elicit biting, have a vertical migration pattern similar to that of the euphausiids. Small copepods, on the other hand, showed evidence of only a slight nighttime increase at the surface.

Feeding by biting, because it is so obviously dependent on visual perception of individual organisms, may not seem compatible with low nighttime levels of illumination, but there is some evidence to the contrary. Hobson (1968) commented that some authors greatly underestimate the extent to which vision can be used at night by both predators and prey. Hunter (1968) showed that juvenile jack mackerel (*Trachurus symmetricus*) obtained 50% of the usual daytime ration when feeding by biting on *Artemia* adults at a light intensity as low as would occur near the surface on a full moonlit night. He noted, also, that more visible energy may exist in the sea than his calculations indicate. Blaxter (1964) listed a number of "visual" feeders that stopped feeding at similarly low light intensities. In regard to the northern anchovy, O'Connell (1963) showed on anatomical grounds that this species has a retina that is probably better adapted

TABLE 5. Hours of feeding necessary for an anchovy weighing 5 g to obtain its daily nutritional requirement (74 mg dry wt) from observed nighttime plankton concentrations for four different percentages of particulate feeding activity. Rules separate the values at 12 and 24 hr.

Zooplankton concentration mg/m ³ dry wt	%	Hr of feeding			
		Filtering only	50% biting	75% biting	99% biting
10	27	84	84	56	<u>42</u>
20	17	42	42	<u>28</u>	21
30	41	28	28	19	<u>14</u>
40	10	21	21	<u>14</u>	11
50	5	17	17	11	9

than that of the jack mackerel for dim-light vision.

From all of the above evidence it seems highly probable that the anchovy can feed by biting at night, and by so doing effectively exceed the limitations of filtering. Loukashkin's (1970) finding that euphausiids and large copepods were the most important items in stomach contents of the anchovy tends to confirm this view.

Leong and O'Connell (1969) evaluated the food potential of zooplankton concentrations in the sea for the anchovy by estimating the hours of filtering necessary to obtain the daily nutritional requirement. Table 5 suggests the way in which different percentages of biting activity might effect this index of food potential, where the different percentages of biting imply that a given concentration is composed of different though undefined proportions of large and small organisms. The percentage distribution for dry weight concentrations is based on the night samples from five plankton pump cruises (O'Connell 1971). Hours of filtering for each dry weight class were calculated on the assumptions that a 5 g anchovy requires 74 mg dry weight of food per day and filters water at the rate of 1.46 liters/minute (Leong and O'Connell 1969). Hours of feeding for percentages of biting were calculated on the basis of the relations suggested in Table 5. That is, ingestion rate is no different for plankton that elicits 50% biting than for plankton that elicits filtering only, but varies proportionately from a factor of one at 50% biting to a factor of two at 99% biting. Feeding duration is inversely proportional to feeding rate.

The calculated values, which are separated by lines at 12 and 24 hr in the table, indicate that with low biting activity only 15% of the area sampled would have provided the anchovy with its nutritional requirement in one day. The same fraction of the area would have provided the daily requirement in less than 12 hr if the plankton concentrations supported relatively high average percentages of biting. If feeding extended over more than 12 hr with a high percentage of biting most of the time, more than half of the area could have provided the required nutrition. The anchovy may capture large organisms less effectively in relation to density at

night than indicated earlier for simulated daylight conditions, but given the high ratios of euphausiid to small copepod dry weight in night samples, some average percentage of biting well above 50% seems entirely possible. Availability of the daily nutritional requirement would also tend to be widened if the anchovy utilizes phytoplankton along with zooplankton. These considerations suggest that plankton is usually adequate for the nutritional needs of the anchovy in a large part of the surface waters off southern California.

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A LABORATORY STUDY OF PARTICULATE AND FILTER FEEDING OF THE PACIFIC MACKEREL, *SCOMBER JAPONICUS*

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ABSTRACT

In laboratory feeding trials Pacific mackerel, *Scomber japonicus*, averaging 147 g in weight did not respond to *Artemia* nauplii, but did capture *Artemia* adults by biting (particulate feeding) when density was 1 or 2/liter and by filtering when density was 22 to 112/liter. Particulate feeding is described by $N_F = 60.3tD$, where N is the number of *Artemia* ingested in t minutes at D numbers per liter. Filter feeding is described by $N_F = 23,788 (1 - e^{-0.0036t\sqrt{D}})$, where 23,788 is an asymptotic estimate of the number of *Artemia* in the digestive tract at full capacity.

The results suggest that the mackerel utilizes only the larger of the planktonic crustaceans, such as euphausiids, in the sea. For the relatively low average densities of such organisms the derived equations indicate that the mackerel could not obtain its daily nutritional requirement, estimated to be 8% of body weight, in less than 24 hr of feeding. Though the daily requirement could be obtained in much shorter periods, perhaps by filter feeding, if such crustaceans are encountered in aggregations of considerably higher density than reflected by area averages, it is probable that the mackerel must often depend in part on such larger organisms as fish to fulfill its needs.

Comparison of the mackerel ingestion rates to those for the smaller northern anchovy indicates that while the individual mackerel may generally capture a greater proportion of the large crustaceans encountered than the anchovy, the proportion captured would have a relatively lower nutritional value for the mackerel.

The Pacific mackerel, *Scomber japonicus*, is one of several pelagic schooling fishes of the eastern temperate Pacific which feed on zooplankton, but it does not depend entirely on zooplankton. Fitch (1956) reported that stomach contents contained about 30% larval and juvenile fish by volume, with the remainder composed largely of such crustaceans as mysids, copepods, and euphausiids. Frey (1971) commented that larval and juvenile fish appear to be the most important food, but that the mackerel relies heavily on euphausiids at times. Hatanaka et al. (1957) showed that *S. japonicus* in coastal regions of Japan consume mainly small anchovies in the late summer and autumn and euphausiids in other seasons. The biomass of euphausiids con-

sumed annually was estimated to be three or four times that of anchovies.

In addition to being the dominant element in the diet of *S. japonicus*, the larger crustaceans are an important class of food for a number of other pelagic schooling fishes. The jack mackerel (*Trachurus symmetricus*) is known to feed heavily on small fish and squid at times (Fitch, 1965), but about 70% of stomach contents by volume is euphausiids (Carlisle, 1971). The Pacific sardine (*Sardinops caerulea*) feeds largely on copepods smaller than those consumed by the jack mackerel but is occasionally gorged on euphausiids, and these average about 5% of stomach contents by volume (Carlisle, 1971). The northern anchovy (*Engraulis mordax*) consumes phytoplankters and small zooplankters, but large copepods and euphausiids appear to be the most important food items (Loukashkin, 1970). Thus while all of these species prey on

¹ National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southwest Fisheries Center, La Jolla, CA 92037.

large crustaceans, the latter do not necessarily make an equivalent contribution to their diets. It is probable that the segment of the biota represented by such crustaceans in the sea is a food source of different potential for different fishes.

Assessing the food potential of large crustaceans for the Pacific mackerel, or any of the above teleosts, requires a knowledge of the density levels of such crustaceans in the sea and of the rates at which the organisms can be captured in relation to density. Leong and O'Connell (1969) determined by a laboratory study the rates at which the northern anchovy feeds on *Artemia* nauplii by filtering and on *Artemia* adults by biting (particulate feeding), and O'Connell (1972) showed that the two kinds of feeding activity in a small school varied with the relative abundance of the two sizes of *Artemia*. The present study was undertaken to obtain comparable information for the Pacific mackerel, using *Artemia* as the food. The results are discussed in respect to the densities of large crustaceans in the sea and in respect to the feeding rates of the anchovy.

METHODS

Feeding trials were carried out in an arrangement of two plastic pools with a connecting trough and gates (Leong and O'Connell, 1969; O'Connell, 1972). The pools were supplied with a continuous flow of filtered sea water and each contained 4.5 m³ of water at a depth of 0.61 m (2 ft). They were under a 12-hr day, 12-hr night cycle of illumination, but all trials were carried out during the day. Temperature varied from 16° to 19°C.

A school of about 160 mackerel was acclimatized in the pool arrangement with the gates open for about 2 weeks and then confined to one pool before the study started. The fish averaged 222 mm (202 to 247 mm) in standard length and 152 g (100 to 225 g) in weight. The latter average is based on weights taken at the end of each feeding trial and included digestive tract contents, which were later found to range from 0.1 to 21.8 g. These values were subtracted from the measured fish weights to obtain estimates

of the weights before feeding. The subsequent analysis involves the adjusted weights, which averaged 147.3 g.

All feeding trials were preceded by at least 24 hr without feeding, which was enough to produce virtually empty digestive tracts in preliminary investigations. For each trial the water flow was turned off, and four fish were diverted from the holding pool to the trough and then admitted to the prepared food situation in the other pool where they were allowed to feed for a given number of minutes. Closing of the gate after admission initiated the time period and introduction of a hinged crowder, which was rapidly closed to trap and remove the fish, terminated the time period. The fish were killed in less than 2 min after introduction of the crowder, immediately measured and weighed, then placed in jars of 10% Formalin with the body cavity opened.

Though the study is concerned primarily with feeding on *Artemia* adults, a few feeding trials were carried out with newly hatched *Artemia* nauplii, which averaged 0.65 mm in length, to document the response of the mackerel to very small crustaceans. The densities in the water were estimated from subsamples, and quantities in the digestive tracts were estimated by total counts or volumetric aliquoting, as described by Leong and O'Connell (1969).

Feeding on *Artemia* adults is based on digestive tract contents of four fish in each of 28 trials, with each trial representing a different combination of food density and feeding time (Table 1). The food situation was established for each trial by placing a given wet weight of *Artemia* adults in the experimental pool and dispersing it gently with wide-mesh dip nets just before admitting the fish. The weights given under food quantity are the wet weights introduced at the start of each trial. These were selected after preliminary observation to include the highest and the lowest levels that could be managed conveniently. The multiplication factors given in certain cells of the table indicate the number of times the specified weight was introduced into the pool during the trial, e.g., 20 g was introduced six times, or at 15-min intervals, during the 90-min trial. This was done to sustain the nominal food den-

TABLE 1.—The array of trials with respect to food density and feeding duration. Number/liter is the nominal density for the weight introduced.

Quantity of <i>Artemia</i>		Minutes of feeding					
Total weight	Number liter	2.5	5	10	30	60	90
g							
10	1	1	1	1	1(3×) ¹	1(6×)	1(9×)
20	2	1	1	1	1(2×)	1(4×)	1(6×)
200	22	1	1	1	1	1	1
590	66	1	1	1	1	1	1
1,010	112	1	1	1	1	--	--

¹ The multiplication factors show the number of times, at equal intervals, that the specified weight was introduced during the trial to maintain the nominal density. See text.

sity over long periods at the lower food density levels. Introduction of food during the trial, and even brief dispersion with the wide-mesh net, did not appear to distress the fish and scarcely interrupted their feeding activity.

The intervals of food introduction for the lower density levels were determined from a preliminary study. During a 30-min trial with 20 g of *Artemia*, e.g., feeding activity declined sharply after 15 min, and average digestive tract contents did not differ from that for a trial of 15 min. A trial of 30 min with two introductions of 20 g showed approximately double the digestive tract contents of the above two. The 10-min interval for 10 g introductions was established from similar considerations. Food availability remained high throughout the trials at the three higher density levels.

The nominal densities of *Artemia* shown in Table 1 are based on the volume of the pool and a conversion factor of 500 *Artemia* adults/g wet weight. The conversion factor is an average derived from samples from the several batches of *Artemia* delivered to the aquarium. Portions of these samples also indicated that individuals averaged 4.5 mm in length and 0.48 mg dry weight.

The quantities of *Artemia* in the digestive tracts of the fish were estimated separately for the mouth, the esophagus and stomach combined, and the anterior and posterior halves of the intestine. The contents of the esophagus and stomach were weighed. Numbers in the various sections were estimated by total count where quantity was low, but by counts from aliquots where the quantity was large. These data indi-

cated that the weight of ingested *Artemia*, determined 2 to 6 months after preservation, was 25 to 50% lower than the weight of the live organisms. Digestion and leaching by Formalin may have been responsible for such loss. Since the weights of food in the digestive tracts could not be considered representative of the weights of food consumed, the analysis was carried out on the numbers of organisms in digestive tracts.

Values for all sections of the digestive tract were pooled to obtain estimates of total digestive tract contents, the primary entity in analysis. The numbers found in the mouth varied from less than 1 to 53% and averaged 18% of total digestive tract contents. This percentage, furthermore, varied with food density, increasing from 4% at the 10 g level to 41% at the 1,010 g level. It is presumed that the contents of the mouth were accumulations to be swallowed and/or material regurgitated during capture. Proportions in the intestine were considerably lower and will be described later.

RESULTS

RESPONSE TO *ARTEMIA* NAUPLII

Three trials were carried out with newly hatched *Artemia* nauplii as the only available food. In two cases the average densities of nauplii were about 190/liter and 230/liter, and groups of four fish showed no recognizable feeding activity during 30-min periods of exposure. In the third case density was a little more than 200/liter and a group of approximately 50 fish showed no feeding activity. The stomachs of five fish from these trials contained no nauplii, although a few nauplii were found on the gill rakers of two of them.

One trial was carried out with *Artemia* adults and nauplii both present in the water. The density of adults was 22/liter and the density of nauplii was 185/liter. After feeding for 5 min, four fish averaged 2,334 *Artemia* adults and 823 *Artemia* nauplii (635 to 1,083) in the mouth, stomach, and esophagus combined. The bulk of both sizes of organism was in the stomachs.

From these results it is evident that while the Pacific mackerel did not respond to nauplii alone,

it did ingest them along with the larger *Artemia* when both were present in the water. However, the dry weight of the nauplii ingested would be about 0.1% of the dry weight of the adults ingested. It appears, also, that the uptake of nauplii was only about 4% as efficient as the uptake of adult *Artemia*, i.e., the number of nauplii per fish represents 4.4 liters of water in the pool, while the number of adults per fish represents 106 liters.

Yasuda (1963) obtained results comparable to the above for *S. japonicus* 120 to 130 mm in length. He found that the mackerel did not eat brine shrimp (0.38 mm in length and presumably nauplii) as did anchovies (*Engraulis japonica*) and even horse mackerel (*Trachurus japonicus*) of approximately the same length. The spacing between gill rakers and gill raker processes was shown to be smaller in the latter two species than in the Pacific mackerel.

RESPONSE TO ARTEMIA ADULTS

The 28 trials in which *Artemia* adults were the only available food showed that feeding was particulate at the two lower density levels and filtering at the three higher density levels. Particulate feeding is the capture of individual organisms by directed biting. Filter feeding is the process of straining organisms from the water as it passes through the gill rakers while the mouth remains open. The duration of mouth opening was 1 to 3 sec, and such mouth openings occurred almost rhythmically 15 to 20 times/min. Filtering, however, was sustained for only a limited time, and this time varied inversely with density level of the food. It lasted 30 min at 22 *Artemia*/liter, 20 min at 66 *Artemia*/liter, and about 15 min at 112 *Artemia*/liter. At these times the fish noticeably reduced swimming speed and shifted to particulate feeding. Though particulate feeding appeared to be less vigorous under these circumstances than at the two lowest food densities, complete cessation of feeding did not occur in any of the trials.

The trial groups of four fish evidenced some discomfort upon encountering the highest food density, 112 *Artemia*/liter. Swimming speed

and coloration showed less increase than at other densities, and filtering intervals were shorter and less rhythmic. A school of about 70 fish introduced to this highest density, on the other hand, exhibited strong rhythmic filtering accompanied by marked intensification of color and increased swimming speed. Though digestive tract contents from the fish of this group were not significantly greater than for the four-fish group after 5 min of feeding, the larger group virtually eliminated the available food in this time while the smaller group did not noticeably affect its density.

Preliminary analysis indicated that there was no confounding of size of fish with density levels and suggested that the larger fish tended to consume slightly more food at all densities. Hence, estimates of total digestive tract quantities were standardized to the average adjusted weight of all fish (147.3 g) by simple proportion. The means and standard errors of the standardized numbers are shown for each trial in Table 2. The greatest change in a trial average resulting from standardization was 20% of the original estimate, and the change was 5% or less for half of the trials. Standardization also affected the estimates of variability, but only to the extent that the coefficients of variation averaged 1% higher.

A separate analysis for each of the food density levels indicated that digestive tract contents increased proportionately with time at the two lower densities, but increased exponentially toward an asymptotic value at the three higher densities. It was also evident that the density-specific rates of increase varied directly with density for the two lower levels and with the square root of density for the three higher levels. The modes of food accumulation for the two density ranges can therefore be expressed as

$$N_P = \alpha t D \quad (1)$$

$$\text{and} \quad N_F = N_\infty \left(1 - e^{-\beta t \sqrt{D}} \right) \quad (2)$$

where N_P = number of organisms in the digestive tract after t minutes of particulate feeding,

TABLE 2.—The average fish weight and the mean ($\bar{X}$) and standard error (SE) of the standardized number of *Artemia* in the digestive tract for each trial.

Density Number/ liter	Feeding duration	Number fish	Average fish weight	Number in digestive tract	
				$\bar{X}$	SE
1	min		g		
	2.5	4	125	149	60
	5	4	130	299	168
	10	4	136	572	86
	30	4	134	2,280	373
	60	3	135	3,430	342
2	90	4	150	5,620	216
	2.5	4	149	254	37
	5	4	148	695	81
	10	3	149	1,530	163
	30	4	123	4,636	583
	60	4	157	5,790	684
22	90	4	149	11,325	1,204
	2.5	2	136	745	263
	5	4	159	2,013	101
	10	3	141	4,399	270
	30	3	135	10,893	790
	60	4	165	15,664	648
66	90	4	152	18,079	1,143
	2.5	3	159	1,502	197
	5	3	139	4,041	409
	10	4	158	5,232	858
	30	4	174	9,863	990
	60	4	158	12,676	484
112	90	4	168	15,723	605
	2.5	3	145	3,079	936
	5	3	155	3,617	447
	10	4	139	7,629	982
	30	4	147	15,845	2,600

N_F = number of organisms in the digestive tract after t minutes of filter feeding,

D = the nominal density of food in numbers per liter,

N_∞ = asymptotic number of organisms in the digestive tract at full capacity,

α = specific feeding rate, and

β = instantaneous feeding rate.

Fitting all of the data in the two low density series with equation (1) and those in the three high density series with equation (2) resulted in a satisfactory fit for the low density group but not for the high density group. Calculated values tended to be lower than trial values for the 22 *Artemia*/liter series, and higher than trial values for the 66 *Artemia*/liter series, particularly for the longer time periods. The difficulty arises from the fact that average quantities in

the digestive tracts were lower for the 66 *Artemia*/liter level than for the 22 *Artemia*/liter level in the 30-, 60-, and 90-min trials. The reason for this is not known, but examination of the quantities in the anterior and posterior halves of the intestine for all trials (Table 3) offers a plausible explanation.

TABLE 3.—Average number of *Artemia* in anterior (A) and posterior (P) halves of intestine for each trial.

Time	Density				
	1	2	22	66	112
2.5 A	0	15	9	33	300
P	0	0	0	0	0
5.0 A	0.3	15	108	101	175
P	0	0	0	0	0
10 A	1.8	50	57	215	467
P	0	0	0	10	59
30 A	50	51	320	1,077	1,265
P	0	0	36	327	245
60 A	0.7	165	830	569	
P	0	45	720	714	
90 A	141	209	890	937	
P	4	339	385	722	

At 22 *Artemia*/liter the maximum quantity in the intestine is reached at 60 min, and at 66 *Artemia*/liter the maximum is reached at 30 min. Fluctuations in the two halves of the intestine thereafter suggest posterior movement of material and intermittent elimination. This is corroborated by visual observations made during the trials. The earliest detected defecations were at 50 min for the 22 *Artemia*/liter level and at about 30 min for the 66 *Artemia*/liter level. No defecation was detected in the trials at 112 *Artemia*/liter, which did not go beyond 30 min. The quantities in the intestine suggest that rate of movement of material into the posterior part of the intestine approached the maximum at 66 *Artemia*/liter and that defecation might not start any sooner at 112 *Artemia*/liter than at 66 *Artemia*/liter.

From these data it is reasonable to suppose that beyond 30 min the time-specific losses by defecation would be greater for the 66 *Artemia*/liter series than for the 22 *Artemia*/liter series, and negligible for the two lower density levels.

On the supposition that the greatest underestimates of total amounts consumed occurred in the three longest time periods of the 66 *Artemia*/liter series, equation (3) was refitted to

TABLE 4.—Estimated parameter values and 95% confidence limits for density series separately and pooled under particulate and filter feeding.

Artemia/liter	Particulate feeding	
	Intercept	Slope (α)
1	46.8 (—316; 410)	61.5 (53.5; 69.5)
2	181.3 (—1,004; 1,367)	58.5 (45.9; 71.1)
Pooled	0 assumed	60.3 (56.3; 64.3)

Artemia/liter	Filter feeding	
	Asymptote (N_{∞})	Instantaneous feeding rate (β)
22	20,322 (16,736; 23,908)	0.0052 (0.0031; 0.0074)
66	15,384 (13,991; 16,778)	0.0045 (0.0035; 0.0060)
112	22,050 (16,999; 27,102)	0.0040 (0.0029; 0.0059)
Pooled ¹	23,788 (21,802; 25,775)	0.0036 (0.0032; 0.0042)

¹ The pooled array under filter feeding does not include the 30-, 60-, and 90-min trials for 66 *Artemia*/liter.

the data for the higher density levels with these three trials removed. The estimated parameters are shown, along with those for the lower density levels, and also for the density levels individually, in Table 4. Since the individual series under particulate feeding did not have intercepts that differed from zero, the parameters for the pooled array were estimated with the intercept assumed to be zero. Goodness of fit for the combined data in both density groups was judged satisfactory; in Figure 1 the calculated curves are compared to the standardized trial means and standard errors for each density series. The equations for the two feeding modes can be stated as

$$N_P = 60.3tD \quad (3)$$

$$\text{and} \quad N_F = 23,788 \left(1 - e^{-0.0036t\sqrt{D}}\right) \quad (4)$$

The asymptotic level, 23,788 *Artemia*, is indicative of the maximum capacity of mackerels at an average weight of 147 g. On the basis of the wet weight of *Artemia*, 500 individuals/g, maximum capacity would be 48 g, or 32% of fish weight. This is about double the greatest weight of fish food removed from the esophagus and stomach, but the two kinds of estimate are not necessarily inconsistent. As suggested earlier, the weights of the digestive tract contents may have underestimated the weights of *Artemia* in the live state by 25 to 50% because of digestion and leaching in Formalin. The estimate given here is based on weight of live organisms. Since digestion is going on during protracted feeding,

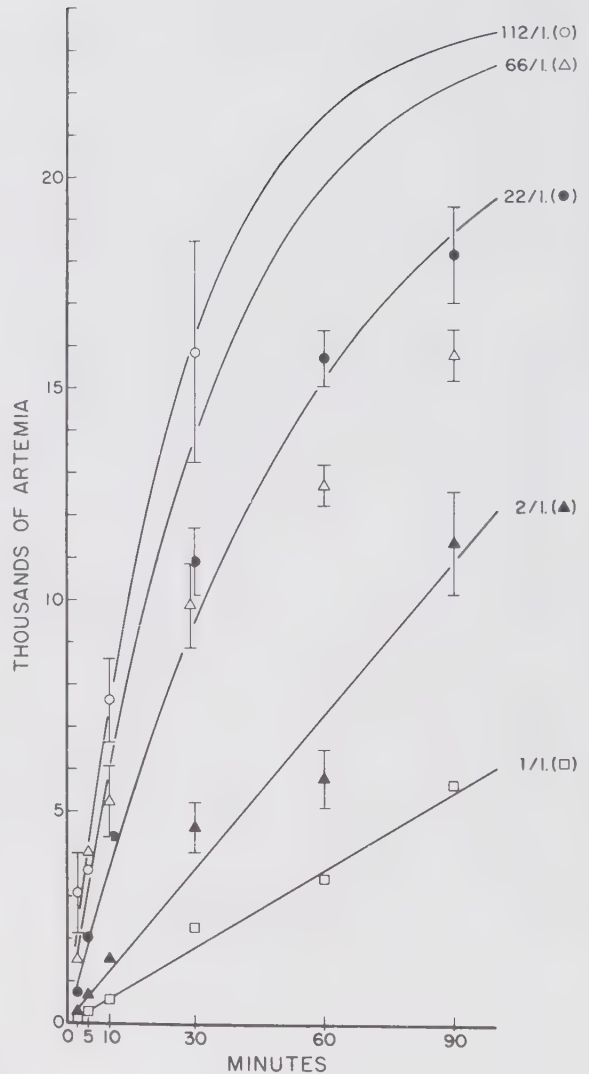


FIGURE 1.—The number of *Artemia* in digestive tracts for different density levels in the water and for different feeding durations. The lines for 1 and 2 *Artemia*/liter were calculated from equation (3) and the lines for 22, 66, and 112 *Artemia*/liter were calculated from equation (4). The symbols associated with each line show averages and standard errors for the trials in that density series. Standard errors smaller than 450 are not shown.

average capacity might well be less than 32% of weight for the asymptotic number specified. The asymptotic number, which was most strongly influenced by the trials at 22 *Artemia*/liter, may slightly underestimate the total number that can be ingested because of losses by defecation.

DISCUSSION

It is evident that *Artemia* adults approximate the smaller crustacean sizes utilized by the mackerel and that the fish resorts to filter feeding to increase the rate of consumption as density exceeds some level where particulate feeding becomes relatively inefficient. The ecological meaning of this feeding pattern is indicated by considering the resulting relation between food density and rate of food accumulation in the digestive tracts in respect to 1) the daily nutritional requirement of the species, 2) the density levels of crustaceans in the sea, and 3) the feeding rates of the northern anchovy (*Engraulis mordax*).

Hatanaka et al. (1957) showed that *S. japonicus* in coastal regions of Japan tend to utilize small fish in late summer and autumn but to rely largely on euphausiids and other crustaceans of similar size in other seasons. They concluded that mackerel a little over 1-year-old and averaging 149 g in weight required 8% of their body weight per day in crustaceans to sustain the growth rate observed in nature, which was estimated as 0.42% of body weight per day. The feeding functions derived in the present study indicate that the times required for the mackerel to obtain this daily requirement at the *Artemia* densities tested, or their equivalent for euphausiids, would be

<i>Artemia</i> /liter	1	2	22	66	112
Euphausiids/liter	0.7	1.3	15	44	75
Minutes	97	49	17	10	7

The equivalent densities for euphausiids are given on the assumption that the mackerel feeding rate is keyed to concentration in terms of biomass rather than to numbers per unit volume as such. Euphausiids near the surface at night in the eastern Pacific, largely *Euphausia pacifica*,

average 6 mm in body length (O'Connell, 1971), and individuals of this length are 3 mg wet weight (Lasker, 1966), or 50% more than the *Artemia*.

The feeding times given above are relatively short, but the *Artemia* densities are much higher than those reported for comparable organisms in the sea. Brinton (1962) showed average densities of *E. pacifica*, largely juveniles, to be about 0.02/liter near the surface at night off southern California. O'Connell (1971) showed an average of 0.03/liter over much the same region, with perhaps 5 to 10% of the area having densities approaching 0.1/liter at any one time. These estimates would be elevated, perhaps doubled, if other large crustaceans were added on a biomass equivalent basis. The highest of these area densities would enable the mackerel to obtain its daily nutritional requirement in about half a day of particulate feeding, but the more commonly prevailing level would not permit the mackerel to obtain its requirement within the space of a day.

In all probability the mackerel obtains much of its needs from euphausiids and other crustaceans of similar size, but there is good evidence that it depends to some extent on larger organisms, such as fish up to one-third of its own body length (Hatanaka and Takahashi, 1960), to secure the daily requirement over a reasonable length of time. Though stomachs tended to be fuller and growth better during the season when the mackerel feeds primarily on fish (Hatanaka et al., 1957), it must be remembered that the 8% daily feeding requirement used here pertains to maintenance and growth when euphausiids were the primary food. If the feeding rates indicated for higher densities of *Artemia* apply for biomass equivalents of much larger organisms, the large capacity of the mackerel suggests that relatively infrequent encounters with such organisms would sustain the daily requirement in an average sense. The present study and that of Kariya and Takahashi (1969) indicate that feeding can be expected to continue towards full capacity regardless of state of fullness when food becomes available.

Though mackerel may have to depend in part on larger organisms, it is possible that the food

potential of the larger crustaceans, and even very young fish, is greater than indicated by average area densities. The definite filtering response of the mackerel, which appears to be an adaptation for capturing the smaller organisms it utilizes at a greater rate than would be possible by biting activity when density is high, implies that high densities are a factor of some consequence in the feeding ecology of the species. One possible explanation is that the various kinds of food organisms tend to be distributed contingently, with aggregations of considerably higher density than reflected by area averages. As Ivlev (1961) demonstrated with carp fry, feeding rate can be expected to increase with degree of aggregation for a fixed quantity of food organisms. Euphausiids have been observed in schools and breeding swarms (Brinton, 1962). More than likely the filtering response is evoked in mackerel with empty or near-empty stomachs by densities not much above the equivalent of 1 or 2 *Artemia*/liter, where rate of effective biting must already be on the order of 60 or more per minute. At 4 to 5 *Artemia*/liter the daily nutritional requirement could be obtained in less than 45 min of filter feeding.

Whereas *Artemia* adults represent the smallest organisms consumed by the mackerel, they represent the largest organisms commonly consumed by the anchovy (Loukashkin, 1970); the latter also consumes phytoplankton and crustaceans less than 1 mm in length by filter feeding. The wet weight quantities of *Artemia* adults consumed at different densities (Table 5), based on the present study for the mackerel and on Leong and O'Connell (1969) and O'Connell (1972) for the anchovy, suggest the differences in utilization and nutritional value of large crustaceans for equivalent age groups of the two species.

The anchovy requires far less food than the mackerel to meet its daily nutritional requirement, and can obtain the necessary quantity in about 20 min when *Artemia* adults are at densities of 1 or more per liter. In this same period the mackerel consumes more than the anchovy at all densities, but not enough to satisfy the daily requirement. When considered in terms of the weight of the two fish, the greater quan-

TABLE 5.—Comparison of *Artemia* adults consumed (mg wet weight) by the 1-year-old mackerel and anchovy for different density levels of *Artemia* in the water.¹

Item	Mackerel	Anchovy
Age in years	1+	1—
Weight $\pm$ g	147	4
Nutritional requirement:		
Percent body weight	8	6.8
mg	11,784	270
Minutes of feeding for nutritional requirement at:		
1 <i>Artemia</i> /liter	97	20
5 <i>Artemia</i> /liter	35	20
Mg <i>Artemia</i> consumed in 20 min with <i>Artemia</i> at:		
0.1 <i>Artemia</i> /liter	240	~152
1 <i>Artemia</i> /liter	600	270
5 <i>Artemia</i> /liter	9,600	270
Mg <i>Artemia</i> consumed/g fish weight in 20 min with <i>Artemia</i> at:		
0.1 <i>Artemia</i> /liter	1.6	~38
1 <i>Artemia</i> /liter	17	68
5 <i>Artemia</i> /liter	65	68

¹ Calculations for the anchovy at age 1+ and weight 7 g show the nutritional requirement and amounts consumed in 20 min at 1 and 5 *Artemia*/liter to be 475 mg, but all other values are the same as for the 4-g anchovy.

ties consumed by the mackerel have a relatively lower nutritional value than those consumed by the anchovy, except, perhaps, at very high densities.

The extreme difference in quantities consumed by the two species at high densities is attributable to the filtering capability of the mackerel, and the failure of the anchovy to filter feed on the larger crustaceans, regardless of density. No meaning can be attached to the small difference at the lowest density level because calculation of the values involved considerable extrapolation. It is nevertheless probable that the anchovy tends to remove large crustaceans at a lower rate than the mackerel at such levels. O'Connell (1972) showed that the feeding activity of the anchovy is likely to be divided between these and the smaller crustaceans captured by filtering if the larger organisms are less than about 5 to 8% of the dry weight of total zooplankton concentration.

From the above considerations it is tentatively hypothesized that the individual mackerel generally utilizes a greater proportion of the large crustaceans in the sea than does the individual anchovy, but that the proportion utilized generally has a relatively low nutritional value for the mackerel.

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COLOR PATTERNS OF SPINNER PORPOISES (*STENELLA* CF. *S. LONGIROSTRIS*) OF THE EASTERN PACIFIC AND HAWAII, WITH COMMENTS ON DELPHINID PIGMENTATION

WILLIAM F. PERRIN¹

ABSTRACT

In this paper, the second of a series on the morphology of small pelagic delphinids by the author, the color patterns of forms of a tropical spinner porpoise *Stenella* cf. *S. longirostris* (Gray) 1828 from the far eastern Pacific, from the waters between North America and Hawaii, and from Hawaiian waters are described and illustrated. The patterns can be analyzed in terms of discrete component systems, and most geographical variation appears to be in a "dorsal field system" overlying a basic general pattern. The overlay is darkest and most extensive in the easternmost form considered and lightest and least extensive in the Hawaiian form. The color patterns of three other delphinids, *Stenella graffmani*, *Delphinus* sp., and *Tursiops truncatus* are analyzed with the component approach, and possible pattern element homologies are defined.

During the course of collecting materials and data for population studies of porpoises involved in the seine fishery for tunas in the eastern tropical Pacific (Perrin, 1970a), I have during the last several years had the opportunity to observe and, less often, to photograph the color patterns of a large number of small pelagic delphinids of several species. Emerging patterns of variation and their possible implications for the systematics of these very poorly known mammals have prompted me to undertake detailed analyses of this body of observations. I have previously (Perrin, 1970b) described the color pattern of the eastern Pacific spotted porpoise *Stenella graffmani* (Lönnerberg) 1934. The primary purpose of this paper is to describe the ontogeny and geographical variation of the color patterns of spinner porpoises of the eastern tropical Pacific and Hawaii. Some description is included

also of variation in the shape of the dorsal fin and correlated features.

The study is based on observations on 157 specimens from the eastern Pacific (Figure 1), of which 41 were photographed, and on photographs and observations of approximately 35 wild and captive animals from Hawaiian waters. Many of the specimens, including most of those from the far eastern Pacific east of Clipperton Island, were examined minutes after capture; others were examined after being held in frozen storage for up to 8 months. Degree of sexual development was determined by histological examination of gonads, with the exception of the large male (Figure 8) from Acapulco, of which only a photograph is available and which was undoubtedly a mature male. Skeletons of specimens of many of the animals illustrated were placed in museums, and the museum numbers are given in the figure captions.

The spinner porpoise of the far eastern Pacific has been referred to *Stenella microps* (Gray) 1846 (Miller and Kellogg, 1955; Hester,

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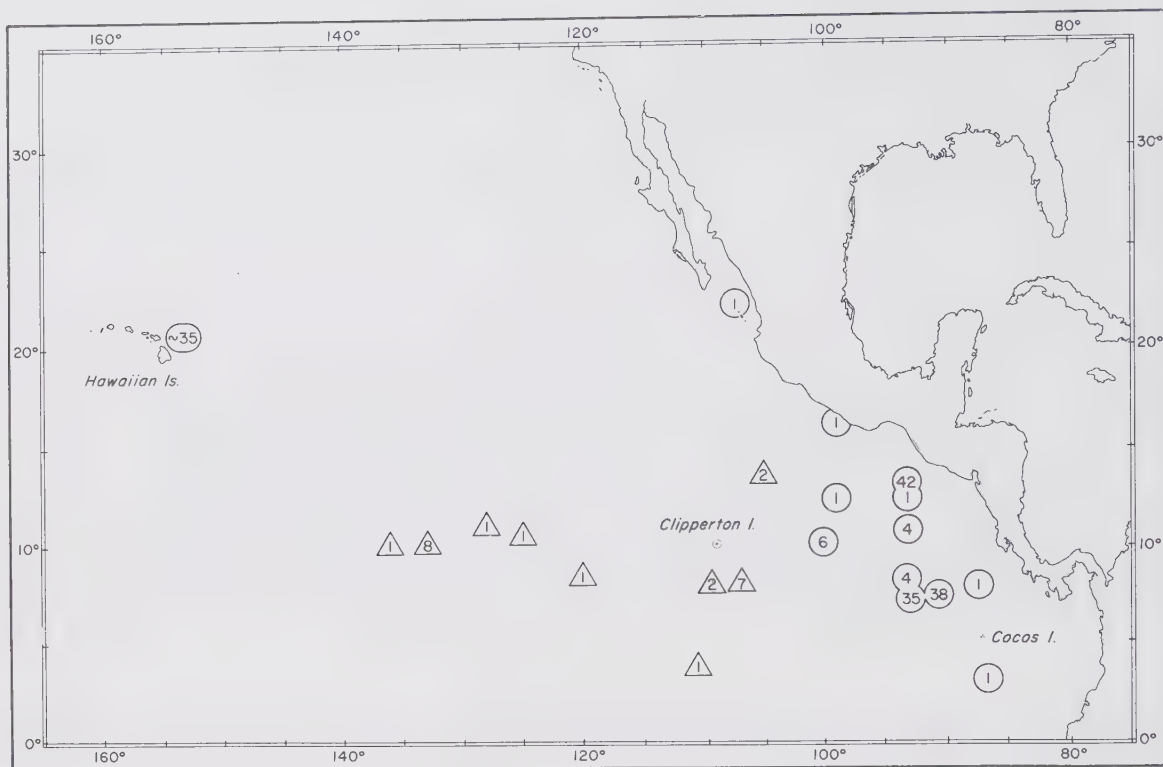


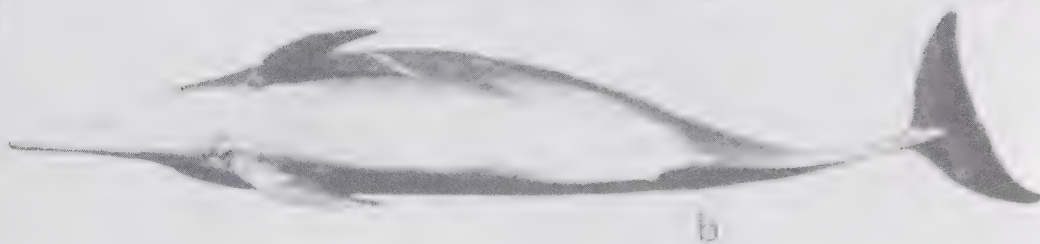
FIGURE 1.—Localities and numbers of specimens examined. Circles in eastern area indicate “eastern spinners”; triangles indicate “whitebelly spinners.”

Hunter, and Whitney, 1963; Nishiwaki, 1967; Pilson and Waller, 1970), but others regard *S. microps* as a synonym of *S. longirostris* (Gray) 1828 (Hershkovitz, 1966; Rice and Scheffer, 1968; Harrison, Boice, and Brownell, 1969). The spinner porpoise of Hawaii has been referred to *S. longirostris* (Hershkovitz, 1966; Nishiwaki, 1967; Tomich, 1969) and to *S. roseiventris* (Wagner) 1853 (Brown, Caldwell, and Caldwell, 1966; Fraser, in Morris and Mowbray, 1966; Rice and Scheffer, 1968). The type localities for *S. microps* and *S. longirostris* are unknown; *S. roseiventris* was described from the Banda Sea, Indonesia. The spinner porpoise of the far offshore areas of the eastern Pacific—called “whitebelly spinner” by fishermen—has not to my knowledge been previously described or referred to any named species. No critical review of the

FIGURE 2.—Calf of eastern spinner. Male, 105 cm total length, from lat 10°30'N, long 92°56'W, April 4, 1968. Perrin field no. CV83; specimen not saved. Shape of dorsal fin is distorted by angle of photograph, should be higher. Photographed minutes after death.

FIGURE 3.—Lateral (a) and ventral (b) views of subadult eastern spinner. Female, 166 cm, from 21°43'N, 106°47'W, February 17, 1967. Marine Mammal Biological Laboratory (Seattle) field no. 1967-102. Skeletal specimen in MMBL collection. Photographed minutes after death.

FIGURE 4.—Adult eastern spinner. Female, 166 cm, from 12°51'N, 93°18'W, April 9, 1968. Perrin field no. CV7; specimen not saved. Photographed minutes after death.



genus has been accomplished since True's work on the Delphinidae published in 1889, when the existence of spinner porpoises in eastern Pacific and Hawaiian waters was not yet known. Evidence presented below concerning geographical variation in pigmentation supports the concept of a single species, highly variable geographically, but taxonomic and nomenclatorial decisions must be based on adequate review of osteological characters, as well as on a broader range of external characters than is considered here. The use of *Stenella* cf. *S. longirostris* therefore is provisional pending the outcome of more extensive studies underway by me and others. A similar situation obtains for the spotted porpoises, and use here of *Stenella graffmani* for the spotted porpoise(s) of the eastern Pacific is also provisional.

DEVELOPMENT AND INDIVIDUAL VARIATION

This account of ontogeny is divided into two parts, one describing development of color pattern as inferred from specimens from the more easterly, relatively nearshore population(s) of spinner porpoise referred to below as the "eastern spinner," and another for specimens of the "whitebelly spinner" of the more westerly, farther offshore areas of the eastern Pacific (Figure 1).

EASTERN SPINNER

Length at birth is 75 to 85 cm (Harrison et al., 1969). The smallest specimen examined was 80 cm long. The smallest specimen photographed was 105 cm long (Figure 2). At this size, the animal is predominantly dark gray. The gray of the dorsum grades imperceptibly into white around the genital region and in a smaller area in the axillary region. A dark gray flipper band from flipper base to the eye-gape region is demarcated above by a narrow, very light line running from behind the posterior insertion of the flipper to the eye and below by a sharp boundary with a light gray gular region. The boundary between the two shades of gray runs

forward between the eye and the end of the gape, becoming obscure in the furrow at the base of the melon. The very light gray below grades anteriorly into darker gray, so that the upper and lower sides of the snout are of about the same shade as the dorsal field. The gape is edged with very dark gray sharply delineated above for about the last third of the gape and below for about the last half of the gape but grading distally above and below into the generally dark gray of the snout. A small eye patch of similar shade is present, and a narrow eye stripe, also of dark gray, runs from the eye patch forward to join the gape mark near the apex of the melon. A similar mark extends from the blowhole to the apex. The margin of a very faintly defined dorsal cape (not visible in the photographs) runs from near the apex of the melon to behind the dorsal fin, passing high over the eye and dipping slightly below the fin to yield a saddle effect discernible only upon very careful scrutiny of a freshly caught animal. Low on the side and adjacent to the genital slit, an elongate, smudge-like mark extends obliquely for several centimeters along a line that if extended in both directions would run from the eye to behind the anus. All appendages are on both surfaces the same gray as the dorsum. The major point of individual variation in animals of this and larger size is in the extent of the ventral and axillary white areas; in some individuals they are larger and may even be confluent, with the dorsal margin extending back from the axillary area to run into the higher genital white area.

The pattern persists as described into subadulthood (subadult being defined as an animal of adult or near-adult size but sexually immature) without change aside from overall darkening (Figure 3). In subadulthood the margins of the ventral and axillary white areas begin to become speckled, and in adults (Figures 4, 5, 6, 7, 8, and 9) the dorsal field, by now very dark gray, appears to encroach on the white areas with spots and blotches to yield a very speckled appearance below (Figure 10). As in younger animals, the major feature subject to individual variation appears to be the extent of the white areas, although in no adult specimens examined were the genital and axillary areas confluent.

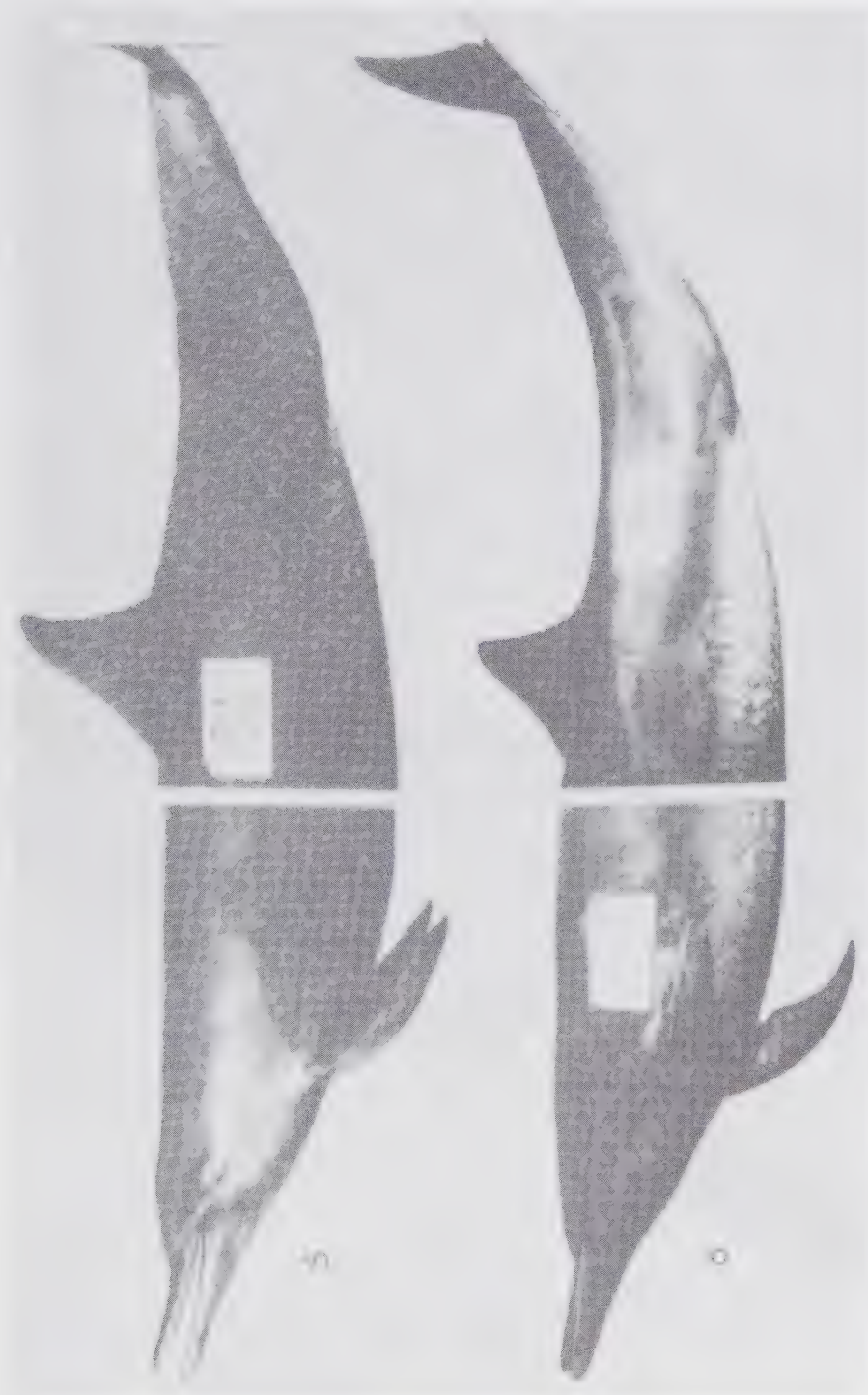


FIGURE 5.—Adult eastern spinner. Female, 160 cm, from 10°30'N, 92°56'W, April 12, 1968. Perrin field no. CV81; specimen not saved. Photographed minutes after death.

FIGURE 6.—Adult eastern spinner. Female, 169 cm, from 10°30'N, 92°56'W, April 12, 1968. Perrin field no. CV82; specimen not saved. Photographed minutes after death.

In the specimens with largest white areas, the region corresponding to that of confluence in some younger specimens was dark gray thickly peppered with light gray spots (Figure 6). In some adults, the gular area is also flecked with light spots (Figure 4). In all adults the degree of contrast between the flipper band and the gular region is much reduced over that in younger animals. The cape remains obscure (see photograph of specimens in water in Perrin, 1968). The oblique mark adjacent to the genital region is obliterated in most adults, but in some can still be faintly discerned (Figure 6). The thin light gray line delineating the upper margin of the flipper band may in adults be prominent or so faint as to appear absent.

In adult males, the dorsal fin is canted forward to a greater or lesser degree (Figures 7, 8, and 9). Development of this feature is correlated with development of a protuberant keel, composed of connective tissue, just posterior to the anus. The function of these features is unknown. However, comparison of the habits of this spinner with those of the Hawaiian spinner, in which the features are very weakly developed (see below), provides a basis for a deductive hypothesis. In the eastern Pacific, spinners commonly occur together with spotted porpoise (*S. graffmani*) in mixed schools comprised of several hundred, or even thousands, of individuals of each species. In Hawaiian waters, spinners and spotted porpoise [there referred to *S. attenuata* (Gray)] do not occur in mixed schools (personal communication from K. S. Norris). In Hawaiian waters, then, most interspecific contacts could be assumed to be head-on and made at some distance, while in the mixed schools of the eastern Pacific interspecific contacts must be relatively more frequent, made at shorter distances, and for the most part lateral. It can be hypothesized that the features function in species recognition in a sexual context, perhaps, for example, to insure that oestrous females make advances to males of the proper species.

WHITEBELLY SPINNER

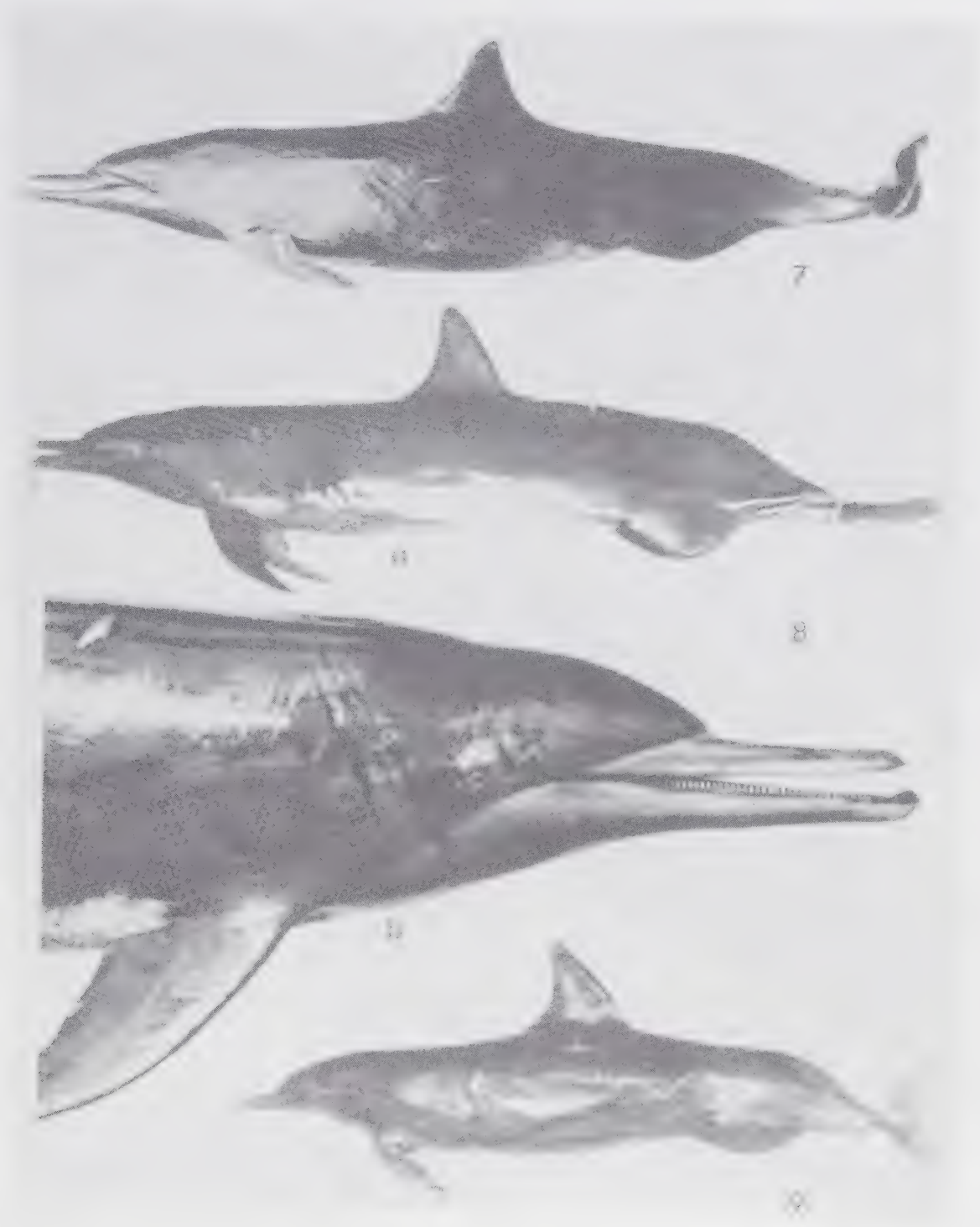
In this animal the ventrum is white. In all young specimens examined, the axillary and gen-

FIGURE 7.—Adult eastern spinner. Male, 175 cm, from 3°N, 87°W, July 19 or 20, 1970. Perrin field no. WFP47; U.S. National Museum no. 396026 (complete skeleton). Photographed after frozen for several months and thawed in water.

FIGURE 8a and b.—Adult eastern spinner. Male from off Acapulco, Mexico. Photographed soon after death. Specimen not saved.

FIGURE 9.—Adult eastern spinner. Male, 186 cm, from 12°20'N, 92°53'W, March 10, 1968; San Diego Natural History Museum no. 21427 (complete skeleton and cast). Photographed in frozen state after several months in frozen storage.

ital white regions were confluent (Figure 11) as in only some young eastern spinners. Again, not much change occurs in the pattern until late subadulthood (Figures 12, 13, and 15) when the margin of the ventrum becomes speckled. The main point of difference between these animals and the eastern specimens, aside from the larger ventral light areas, is that there is much greater contrast between the dorsal cape and the lateral field. The cape can even be discerned in some of the photographs of frozen specimens (Figure 13). In some subadults (Figure 13) an anteriorly narrowing dark gray mark can be seen in the area between the flipper insertions. Other differences between this and the eastern form are discussed below. As in the eastern spinner, individual variation among adults (Figures 16, 17, 18, 19, 22, and 23) is most pronounced in extent of the light ventrum, but the lower end of the range is about equal to the upper end for the eastern spinner. Also again, there is considerable variation in intensity of speckling (compare Figures 16 and 22), and the supraflipper-band stripe may be effectively absent (Figure 19). The flippers are usually dark on both sides, but may be speckled above (Figure



22) and/or below (Figure 21). The oblique mark adjacent to the genital region is obliterated in some adults, but in others (Figure 23) is very clearly delineated.

GEOGRAPHICAL VARIATION

Very young specimens of the Hawaiian spinner (Figure 24, and Figure 7 in Perrin and Hunter, 1972) were not available for examination nor was it possible to determine with certitude the degree of maturity of most of the animals seen. One large male observed (PUKA at Sea-life Park in Waimanalo, Oahu), however, has been in captivity for 5 years and can be presumed to be adult. The major differences between the Hawaiian spinner and the whitebelly spinner of the eastern Pacific are that in the Hawaiian animal the light ventrum extends dorsad nearly to the level of the eye, as it does in its extreme expression in the whitebelly spinner, and is not speckled at the margin. The dorsal fin becomes increasingly erect with development, but is always at least slightly falcate, and the ventral keel associated with triangular and canted fins in the eastern Pacific spinners is all but absent. All contrasts are on the average more pronounced: between cape and lateral field, flipper band and gular area, gape mark and underside of lower jaw. The ventral margin of the cape follows a

FIGURE 10.—Close view of genital region of adult male eastern spinner depicted in Figure 9.

FIGURE 11.—Lateral (a) and ventral (b) views of calf of whitebelly spinner. Female, 105 cm, from 8°N, 109°45'W, March 5, 1969. Perrin field no. PQ11; U.S. National Museum 395601 (complete skeleton). Photographed frozen after approximately 1 month in frozen storage.

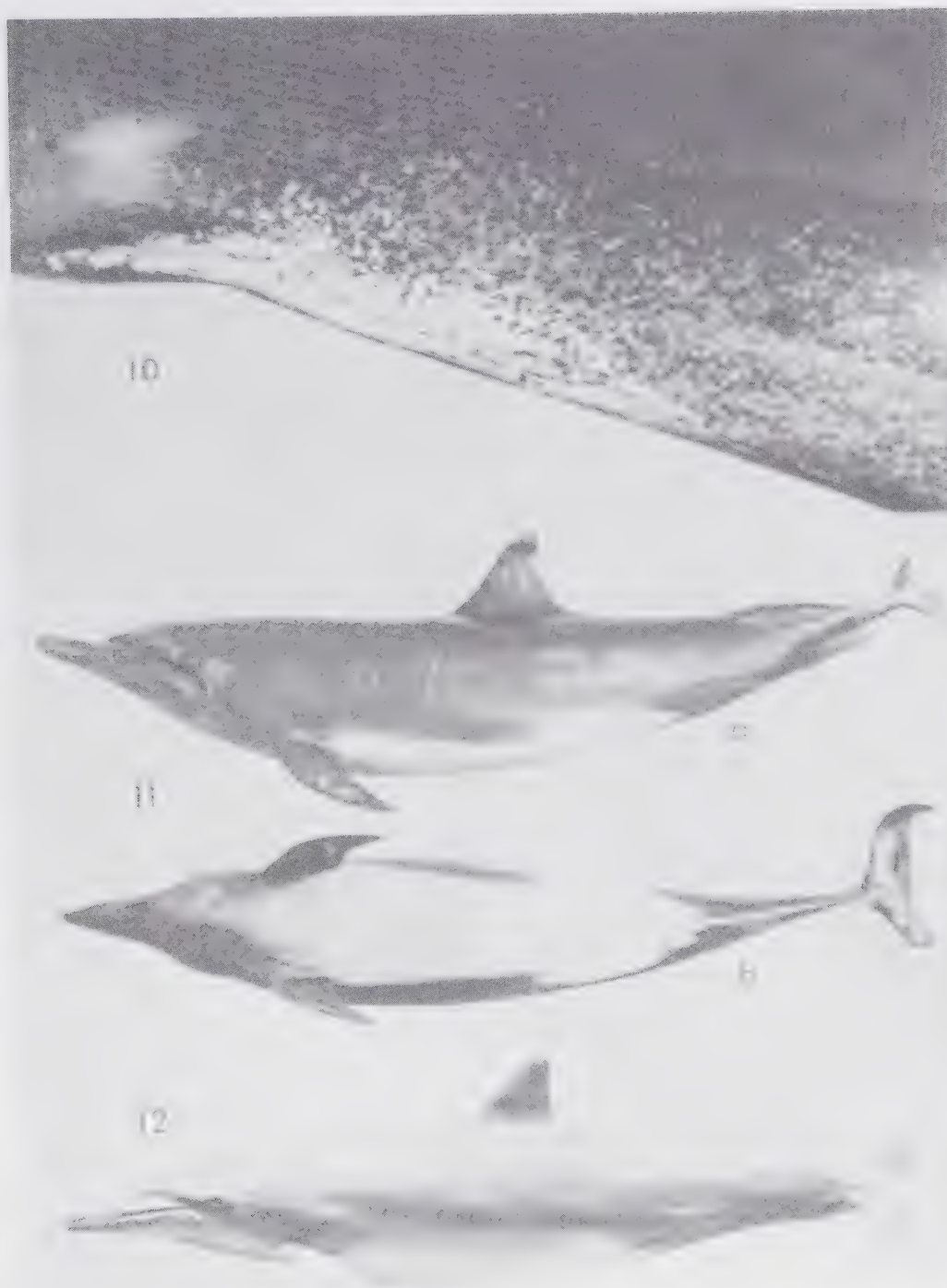
FIGURE 12.—Subadult whitebelly spinner. Female, 129 cm, from 9°47'N, 133°25'W, August 11, 1970. Perrin field no. WFP58; U.S. National Museum 396036 (complete skeleton). Photographed after frozen for several months and thawed in water.

convex smooth curve over the eye in the whitebelly spinner but dips over the eye in the Hawaiian form.

The differences among the whitebelly, eastern, and Hawaiian spinners are summarized in Table 1. These differences appear to be based primarily in differential development. The small subadult of the whitebelly spinner (Figures 12 and

TABLE 1.—Summary of some external features differing between adults of Hawaiian, whitebelly, and eastern spinner porpoise.

Feature	Hawaiian spinner	Whitebelly spinner	Eastern spinner
Contrast of cape with lateral field	Very pronounced	Clearly discernible	Effectively absent
Ventral margin of cape over eye	Dips	Smooth curve, no dip	Obscure
Ventral white field	Extends dorsad nearly to level of eye; margin smooth	Extends dorsad variably nearly to level of eye; margin speckled; genital and axillary areas confluent	Restricted to discrete genital and axillary areas of varying extent; margins speckled
Black snout tip	Present	Variable	Absent
Contrast between flipper band and gular region	High	High to medium	Low
Spots in gular region	Absent	Variable	Variable
Flippers	Dark	Dark or speckled	Dark
Dorsal fin in adult male	Falcate	Falcate to triangular	Triangular to canted
Protuberant ventral keel in adult male	Absent	Small to medium	Small to large



13) more closely resembles the Hawaiian spinner than does the adult, in that the margin of the ventral white field is relatively smooth. The pattern of the fetus of the eastern spinner (Figure 25) is also very close to the Hawaiian pattern, with the tripartite effect of cape, lateral field, and high ventral field being very pronounced. The question of which sort of developmental cline is involved, paedogenesis to the west or gerontogenesis to the east, is however yet an open one and must be settled by consideration of additional lines of morphological and zoogeographic evidence.

Pattern component analysis.—Comparison of the color pattern of a partially albinistic subadult whitebelly spinner (Figure 14) with that of a normally pigmented individual of the same sex and nearly the same length (Figure 13) affords insight into the mechanisms of pattern formation. In the lighter-than-normal animal, the cape, eye patch and stripe, gape mark, dorsal fin, and flukes are as in the normal specimen. The lateral field, flipper band, and oblique genital mark are obscure, and the flippers are white on both surfaces. White brushings sweep up from the edge of the cape at about midlength toward the dorsal fin. From these facts, the inference can be made that the full normal pattern is the result of the combined effect of two independent pigmentation systems, one involving the cape and accessory stripes, eye and gape marks, dorsal fin, and flukes, and the other involving lateral field, flipper band, and flippers. While the genital mark is not apparent in the albinistic animal, the developmental pattern of obliteration through development of the lateral field suggests that it belongs to the cape system. The difference among the Hawaiian, whitebelly, and eastern spinners can be interpreted schematically in terms of these hypothetical systems (Figure 26), allowing a clearer picture to emerge of the possible patterns of geographical variation involved. Since the lateral field appears in this sense to be the lateral portion of a more extensive dorsal field overlaying the cape, it is referred to below as an aspect of a "dorsal field overlay."

Among these three forms, the "dorsal field

FIGURE 13.—Lateral (a), dorsal (b), and ventral (c) views of subadult whitebelly spinner. Male, 164 cm, from 9°47'N, 133°25'W, August 11, 1970. Perrin field no. WFP65; U.S. National Museum 396017 (complete skeleton). Rostrum damaged. Photographed after frozen for several months and thawed in water.

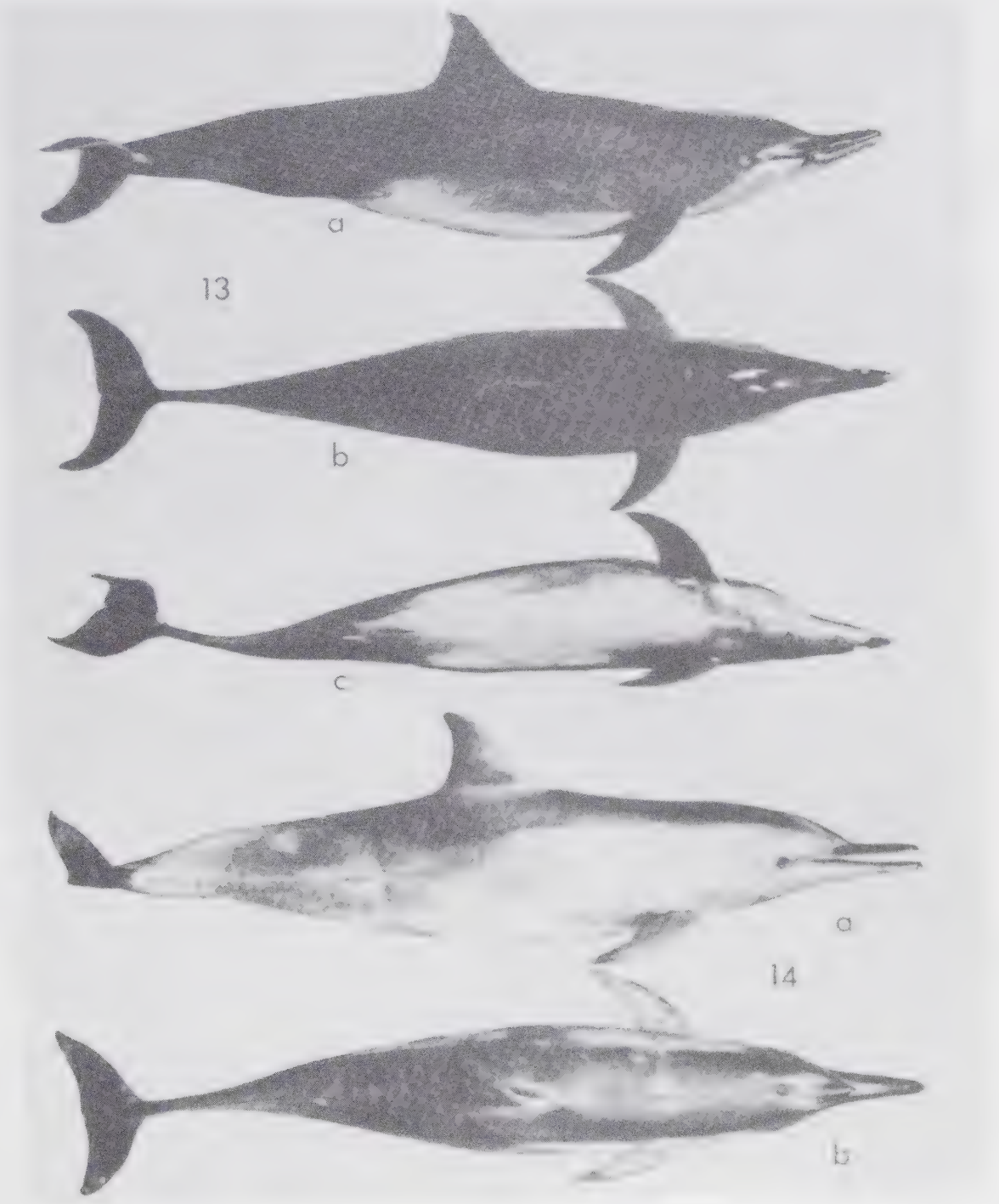
FIGURE 14.—Lateral (a) and dorsal (b) views of albinistic subadult whitebelly spinner. Male, 154 cm, from 10°19'N, 135°38'W, August 5, 1970. Perrin field no. WFP67; U.S. National Museum 396020 (complete skeleton). Compare with normally pigmented animal in Figure 13. Note dark flukes and light flippers. Photographed after frozen for several months and thawed in water.

overlay" is darkest and most extensive in the easternmost form, and least so in the Hawaiian form. It is not yet known whether the three forms represent modes in a geographically continuously varying single species or two or more reproductively isolated allopatric or sympatric populations.

OTHER DELPHINIDS

The color patterns of other closely related delphinids can be similarly dissected into hypothetical component systems. The patterns of three forms of which I have directly examined live or freshly captured dead specimens are analyzed in Figure 27, with an attempt to define possible homologies for the component systems among the species. As the first step in breaking down the patterns into supposedly homologous components, I attempted to define for each a cape with associated markings, similar to that in the albinistic spinner described above.

In the eastern Pacific spotted porpoise, *Stenella graffmani*, (Figure 27, top) the general cape system is very close to that of the spinners, with the cape extending farther ventrad. The dorsal overlay is less extensive than in any of the spinners, and the flipper band runs forward to the gape rather than to the eye. The area of contact between the flipper band and the gape mark in this and in similar spotted porpoise from other



parts of the world is emphasized in many individuals by a zone of lighter pigmentation (see Figures 4 and 6 in Perrin, 1970b; Figure 1 in Best, 1969; and Figure 3 in Nishiwaki, Nakajima, and Kamiya, 1965), which supports the idea of separate origin of the two marks. In the spotted porpoises, the combined pattern systems are overlaid with discrete dorsal and ventral spot systems that to greater or lesser extent obliterate them (Perrin, 1970b).

In *Delphinus* spp. (Figure 27, middle) the dorsal field overlay is less extensive anteriorly than the cape, resulting in invasion of the cape by the ventral field and yielding a four-part criss-cross pattern with zones of black, buff, gray, and white. The deduction to be made is that the whitebelly region represents total lack of pigment, the buff "thoracic patch" (terminology of Mitchell, 1970) represents the color yielded by the pigment of the cape alone, the gray "flank patch" (of Mitchell) that of the pigment of the dorsal field overlay alone, and the black dorsal-most area that of the combined effect of the pigments of the cape and the dorsal field overlay. Chromatographic analysis of pigments present in the various regions and comparison of the results with those of similar tests for other delphinids would contribute to verification or rejection of the suggested homologies.

The pattern of *Tursiops truncatus* (Figure 27, bottom) is very close to that of the spinners in every respect, with the flipper band running to the eye and demarcated dorsally by a narrow light line. The dorsal field overlay of varying darkness extends ventrad to about the same degree as in the eastern spinner. Observation of wild bottlenose porpoise in the eastern temperate and tropical Pacific and examination of some of the thousands of published photographs of animals from around the world lead me to believe that the main component of geographical variation, as for the spinner porpoises, is the extent and darkness of the dorsal overlay. In Hawaiian *Tursiops* that I have observed, the ventral margin was high and sharply defined exactly as in the Hawaiian spinner.

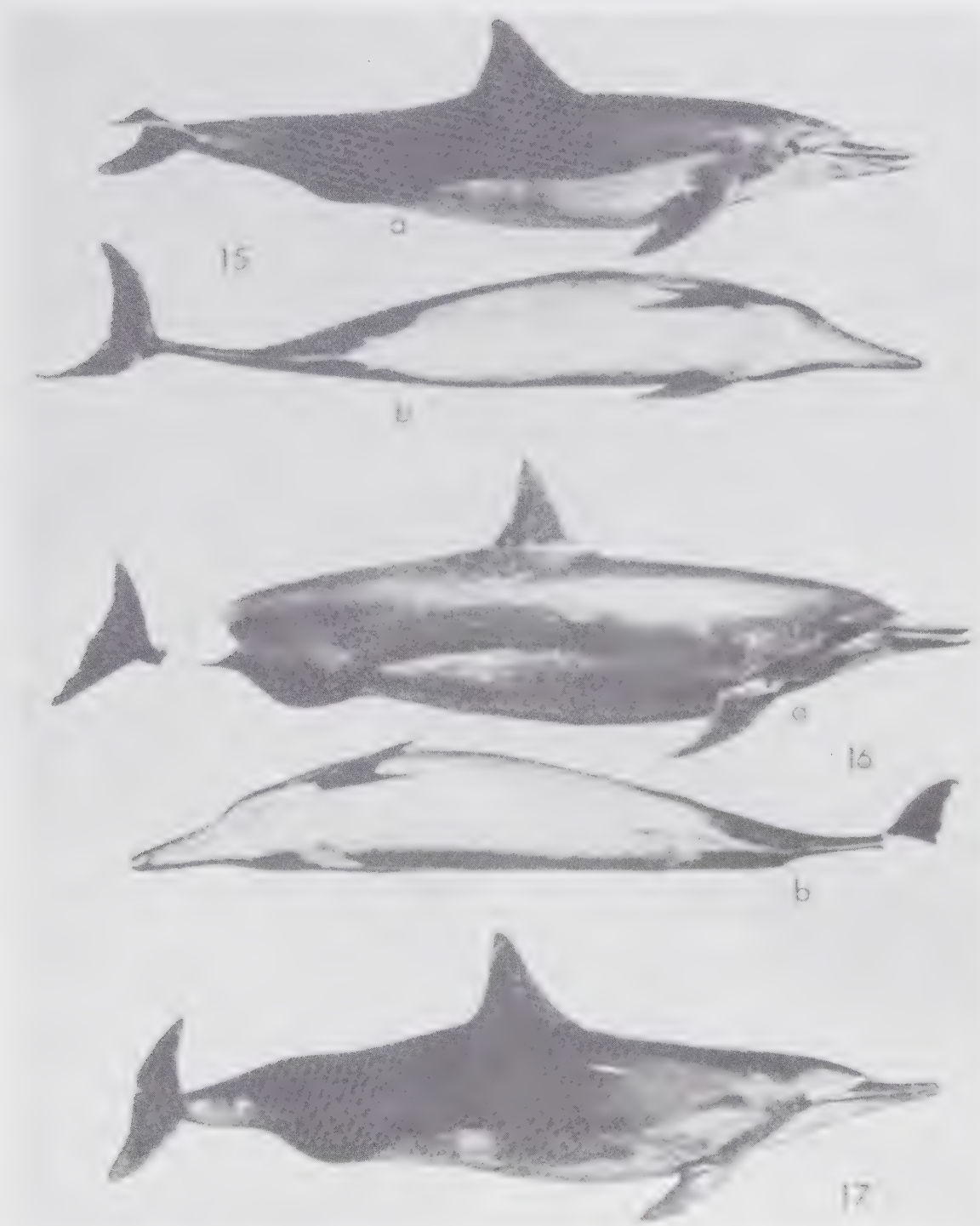
The general cape system common to the four forms discussed above corresponds roughly to the "saddled pattern" described by Mitchell

FIGURE 15.—Lateral (a) and ventral (b) views of subadult whitebelly spinner. Male, 166 cm, from 10°N, 129° or 136°W, August 10-12, 1970. Perrin field no. WFP71; U.S. National Museum 396023 (complete skeleton). Photographed after frozen for several months and thawed in water.

FIGURE 16.—Lateral (a) and ventral (b) views of adult whitebelly spinner. Male, 169 cm, from 9°47'N, 133°25'W, August 11, 1970. Perrin field no. WFP53; U.S. National Museum 396031 (complete skeleton). Photographed after frozen for several months and thawed in water.

FIGURE 17.—Adult whitebelly spinner. Male, 174 cm, from 9°47'N, 133°25'W, August 11, 1970. Perrin field no. WFP76; U.S. National Museum 396170 (complete skeleton). Photographed after frozen for several months and thawed in water.

(1970) as a generalized and probably primitive pattern within the Delphinidae. The "saddled pattern" depicted in his Figure 7, however, is definitely not that of the spinner porpoises, which he included in a group of "saddled" species in his Figure 17. I concur with Mitchell in his selection of the "saddled" condition as a good candidate for a primitive pattern, insofar as his definition of that pattern category pertains to the "general cape system" described here. Lines of evidence presented here leading to this conclusion are the possession in common of a relatively invariant cape system by several delphinid species and the tendency of the cape to be partially marked, distorted, or obliterated in a varying fashion within a species or species group not so much by alteration of its intrinsic form but more by interaction with more plastic overlying systems or (as Mitchell pointed out in the case of the "spinal blaze") by subtraction through invasion by areas of nonpigmentation.

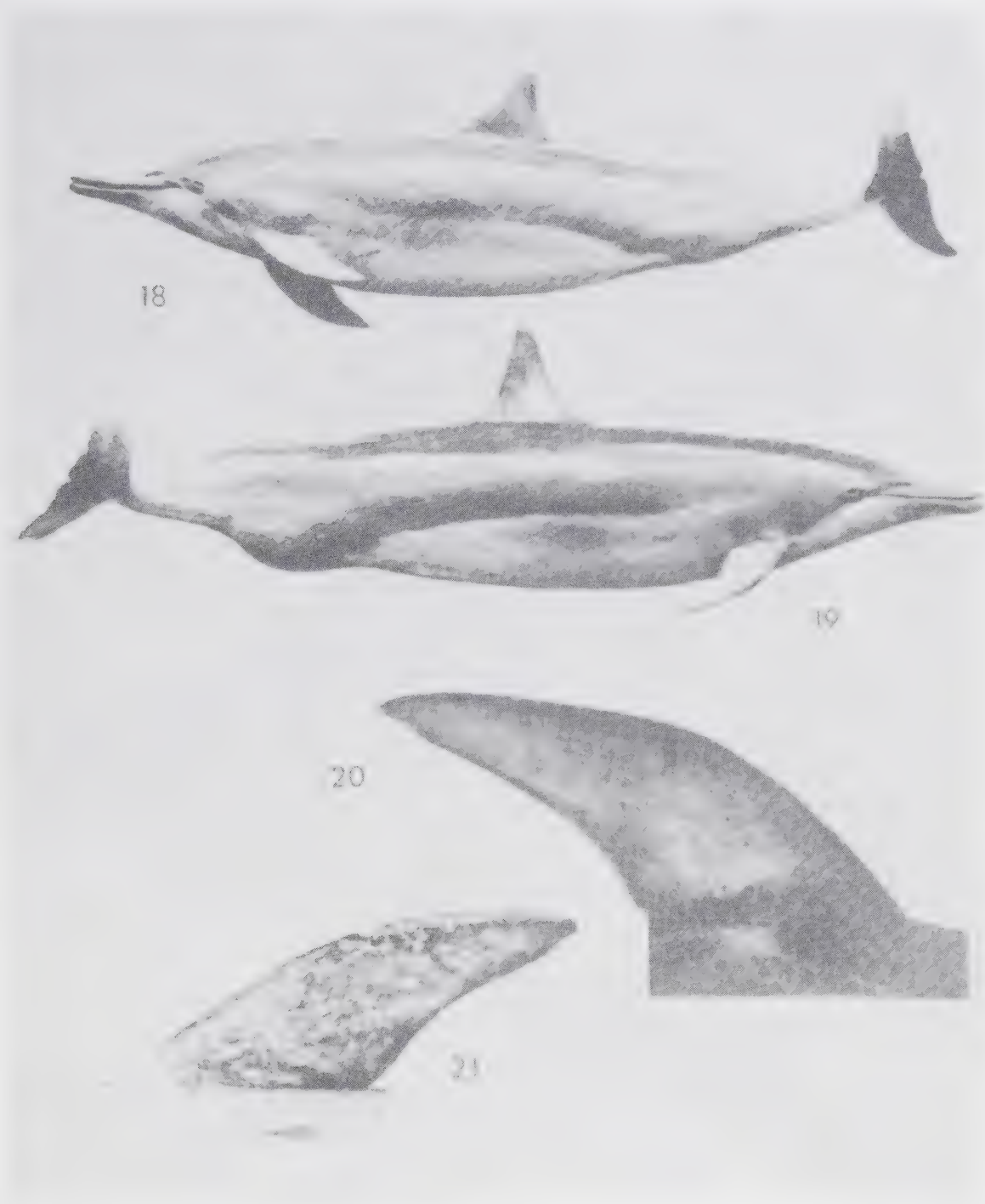


ACKNOWLEDGMENTS

Specimens were collected and examined through the cooperation of the owners, captains, and crews of the tunaboats *Carol Virginia*, *Conte Bianco*, *Connie Jean*, *Conquest*, *Anne M*, *Pacific Queen*, and *Queen Mary*. C. J. Orange, J. S. Leatherwood, and G. D. Sharp collected specimens. D. W. Rice provided the photographs used in Figure 3. J. H. Prescott provided photographs used in Figure 8. K. S. Norris provided photographs used in Figure 24, and arranged for a visit to Hawaii to observe wild and captive spinner porpoise. I am indebted to Bonnie Dalzell for the ideas concerning the possible significance of the canted fin and ventral keel in the eastern spinner. K. S. Norris, E. D. Mitchell, D. W. Rice, C. O. Handley, Jr., and D. K. Caldwell read the manuscript. E. D. Mitchell offered especially valuable criticism.

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- FIGURE 18.—Adult whitebelly spinner. Male, 177 cm, from 9°47'N, 133°25'W, August 11, 1970. Perrin field no. WFP54; U.S. National Museum 396032 (complete skeleton). Photographed after frozen for several months and thawed in water.
- FIGURE 19.—Adult whitebelly spinner. Male, 178 cm, from 10°N, 128° or 136°W, August 10-12, 1970. Perrin field no. WFP52; U.S. National Museum 396030 (complete skeleton). Photographed after frozen for several months and thawed in water.
- FIGURE 20.—Dorsal surface of flipper of specimen depicted in Figure 17.
- FIGURE 21.—Ventral surface of flipper of specimen depicted in Figure 19.
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FIGURE 22.—Lateral (a) and ventral (b) views of adult whitebelly spinner. Female, 179 cm, from 3°20'N, 110°44'W, June 24, 1970. Perrin field no. WFP79; U.S. National Museum 396173 (complete skeleton). Rostrum damaged. Photographed after frozen for several months and thawed in water.

FIGURE 23.—Adult whitebelly spinner. Female, 169 cm, from 8°19'N, 119°15'W or 3°20'N, 110°44'W, June 11 or 24, 1970. Perrin field no. WFP80; U.S. National Museum 396174 (complete skeleton). Photographed after frozen for several months and thawed in water.

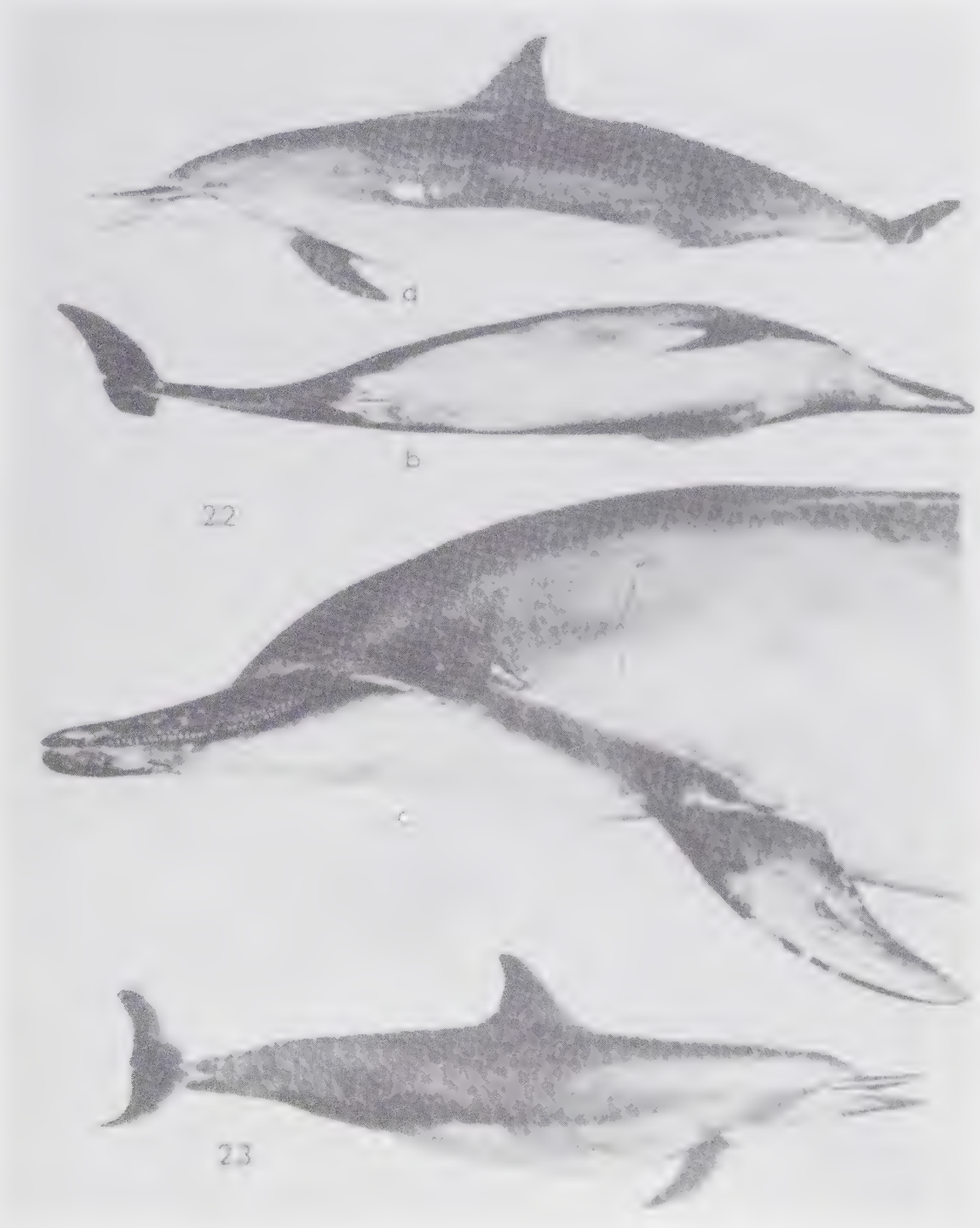




FIGURE 24.—Lateral (a), dorsal (b), ventral (c), and close-up lateral (d) views of Hawaiian spinner porpoise. Subadult male, 179 cm, from Waikiki Beach, Oahu, May 25, 1970. Oceanic Institute field no. OI70-35; specimen stolen during preparation. Photographed 3 hours after death.

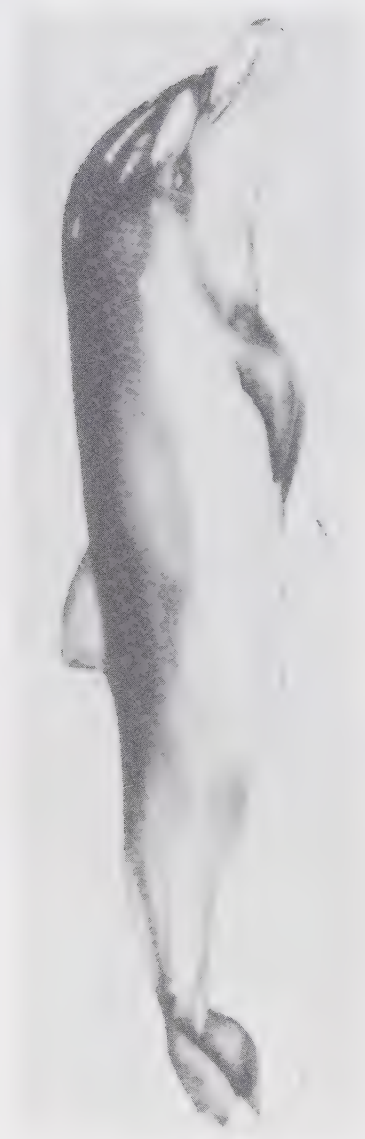


FIGURE 25.—Fetus of eastern spinner. Male, 361 mm, 640 gm, from 9°19'N, 105°20'W, November 10, 1971. Perrin field no. (of mother) WFP187. Specimen at the National Marine Fisheries Service Laboratory, La Jolla, Calif. Photographed underwater after removal from frozen adult, which had been frozen for several months and thawed in water. Dorsal fin folded, and epidermis damaged about head (white areas).

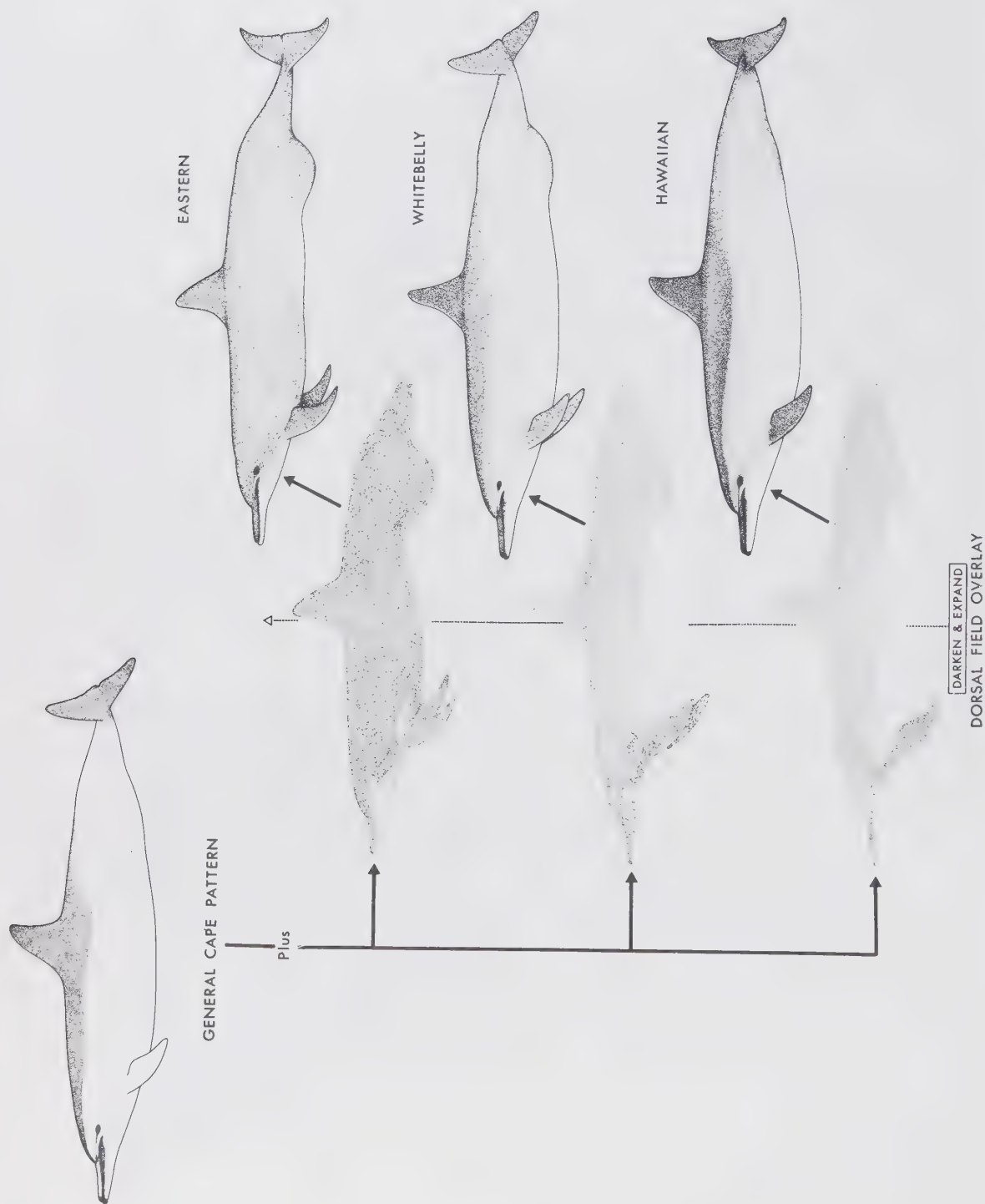


FIGURE 26.—Scheme for analysis of color patterns of spinner porpoises in terms of discrete component systems.

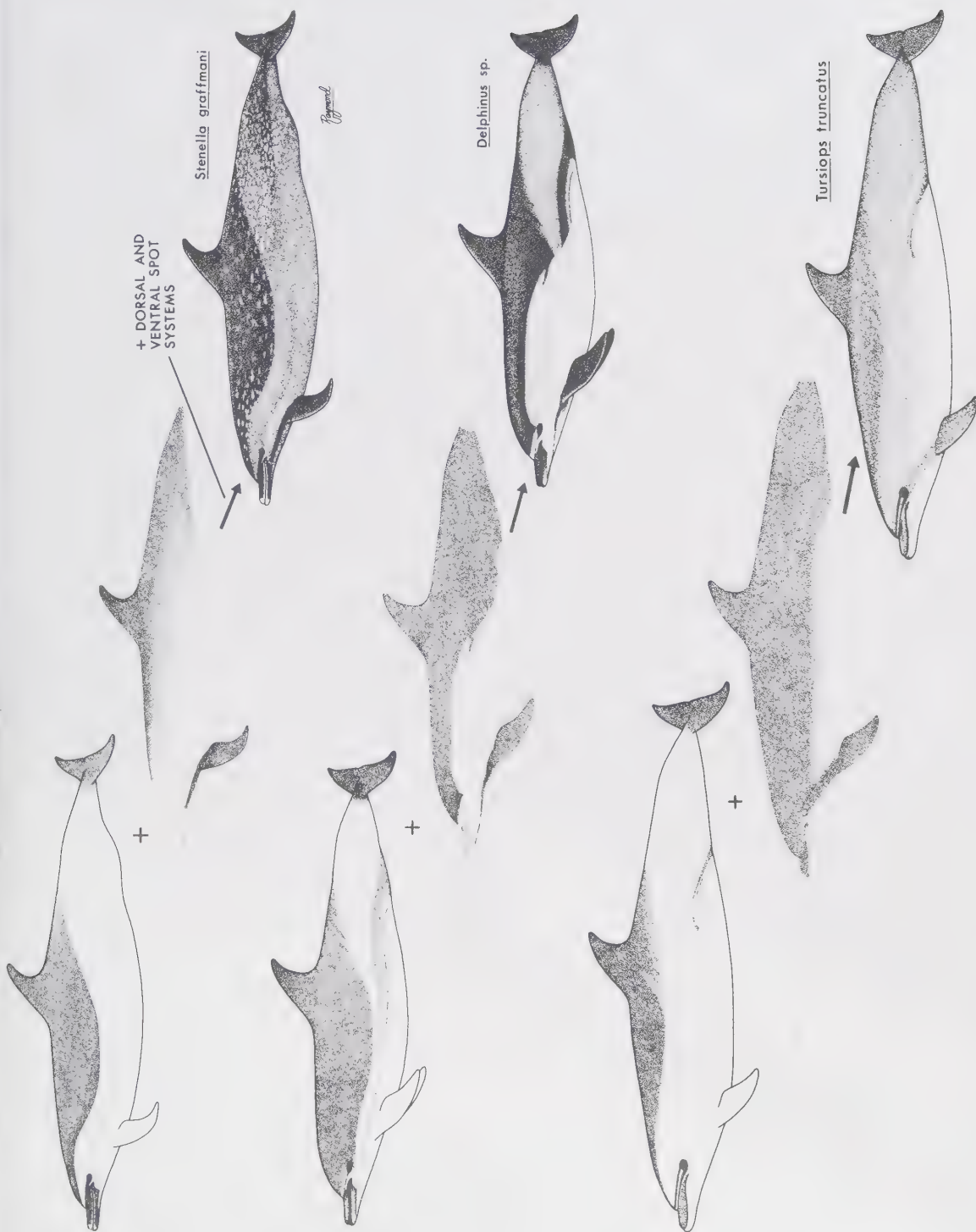


FIGURE 27.—Component analyses of color patterns of *Stenella graffmani*, *Delphinus* sp. (based on observations of specimens taken off southern California), and *Tursiops truncatus* (based on observations of captive specimens from southeast Atlantic coast of United States).

ORGAN WEIGHTS OF NON-CAPTIVE PORPOISE (*STENELLA* SPP.)WILLIAM F. PERRIN¹ AND EDWARD L. ROBERTS²

ABSTRACT: Weights of heart, lungs, liver, kidney, and spleen of 68 eastern Pacific spotted porpoise (*Stenella graffmani*) and 14 eastern Pacific spinner porpoise (*S. cf. S. longirostris*) are presented and related to total body weight. Values of Huxley's growth coefficient α are presented. Adult female spotted porpoise have on the average smaller spleens than adult males; a hypothesis of suppression of antibody production in pregnant females is suggested.

Information on organ weights and on other aspects of the anatomy of non-captive cetaceans is valuable for 3 reasons: 1) to establish norms that may be used in evaluation of the post-mortem condition of animals that die in captivity, 2) to further understanding of the physiology and overall biology of these animals, which is so radically different from that of terrestrial mammals, and 3) to provide comparative data for use in the systematics of the group.

Odontocete cetaceans for which various organ weights have previously been reported include *Phocoena phocoena*, *Tursiops truncatus*, *Lagenorhynchus acutus*, *Delphinus delphis*, *Grampus griseus*, *Delphinapterus leucas*, *Physeter catodon* (Slijper, 1959); *Globicephala melaena* (Cowan, 1966); and, very recently, *Inia geoffrensis* (Pilleri and Gihl, 1969b), and *Stenella styx* [= *S. coeruleoalba* (*fide* Mitchell, 1970)] (Gihl and Pilleri, 1969a). Layne (1965) reported weights of heart, lungs, liver, and kidneys for 1 specimen of *Stenella longirostris*. We report here weights of several organs for 68 eastern Pacific spotted porpoise, *Stenella graffmani* (Lönnerberg, 1934), and 14 eastern Pacific spinner porpoise, *Stenella cf. S. longirostris* (Gray, 1828). Specimens of the spotted *Stenella plagiodon* and *S. attenuata*, both very

similar to the eastern Pacific spotted porpoise, have been or are on exhibit or held captive for research purposes at various institutions on the southeast coast of North America and in Hawaii, respectively. Specimens of *Stenella roseiventris*, very similar to the eastern Pacific spinner porpoise, are currently held by aquaria in Hawaii.

METHODS

The specimens examined were all from the eastern tropical Pacific (Table 1). They were part of a large series of animals gathered for extensive studies of external morphometrics, osteology, parasites, and reproduction, which will be reported elsewhere. The porpoise were captured and killed accidentally during the course of commercial tuna seining operations, such as described by Perrin, 1969. The animals were placed in refrigerated holds along with the tuna and upon return to port were kept in freezers at -18°C until they could be dissected. Before dissection, the specimens

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² Animal Hospital of Fountain Valley, 18542 Brookhurst Street, Fountain Valley, California 92708.

TABLE 1. Collection data.

Date	Locality	Number of specimens		Number of schools
		<i>Stenella graffmani</i>	<i>Stenella cf. S. longirostris</i>	
9 Apr. 1968	12°51' N/93°18' W	36	4	1
12 Apr. 1968	7°11' N/90°32' W	29	2	1
26-27 Mar. 1969	7°47'-8° N/106°36'-106°50' W	3	4	?
28 Apr. 1969	7°40'-8° N/107° W		2	?
5 Apr. 1969	8° N/109°45' W		2	1
Total		68	14	

TABLE 2. Total length, total weight, and organ weights of 68 specimens of *Stenella graffmani* and 14 specimens of *S. cf. S. longirostris*.

Specimen (field no.)/U. S. Nat. Mus. No. (skeleton)	Sex	Total length (cm)	Total weight (kg)	Heart (gm)	Lungs (gm)	Liver (gm)	Kidneys		Spleen (gm)
							Left (gm)	Right (gm)	
<i>Stenella graffmani</i>									
CV 259/395276	M	168	44.6	—	—	1000	(—409—)		43
CV 260/395277	F	175	58.2	—	—	1767	326	312	48
CV 261/395278	F	166	46.8	—	—	1283	182	205	44
CV 262/395279	F	165	43.2	—	—	1065	193	182	44
CV 263/395328	M	176	49.5	—	—	1259	235	251	51
CV 264/395329	M	172	50.0	—	—	1137	247	306	53
CV 265/395330	M	195	76.7	—	—	1727	326	353	54
CV 266/395331	M	168	47.2	—	—	1011	178	199	32
CV 267/395332	M	179	61.7	—	—	1398	246	234	39
CV 268/395333†	F	190	76.3	—	—	1480	250	240	46
CV 269/395334	F	184	59.9	—	—	1476	217	209	31
CV 270/395336†	F	182	70.8	—	—	1304	298	319	36
CV 271/395337	F	182	58.2	—	—	1467	245	251	35
CV 272/395338†	F	185	72.7	—	—	1394	242	—	16
CV 273/395339	M	163	47.2	—	—	1000	220	233	85
CV 274/395385	M	178	53.2	253	—	1153	232	208	24
CV 275/395386	M	157	42.2	230	—	1087	200	247	84
CV 276/395387	M	158	50.0	211	—	1274	216	201	45
CV 277/395388	F	182	59.9	291	—	1396	284	300	38
CV 278/395389	M	163	44.1	207	—	1237	190	199	62
CV 279/395390	M	218	84.0	311	—	1892	477	485	36
CV 280/395391	M	203	82.7	311	—	1961	406	429	46
CV 281/395392	F	174	43.2	214	—	1280	220	227	60
CV 282/395393	F	174	44.1	179	—	1052	207	199	32
CV 283/395394	M	202	79.9	308	—	2195	484	480	50
CV 284/395395†	F	193	71.3	250	—	1371	309	290	30
CV 286/395397	M	165	47.7	199	—	1112	190	233	100
CV 287/395417	M	173	53.6	261	—	1325	260	296	60
CV 289/395594	M	177	48.6	226	1576	1219	227	243	44
CV 290/395595	F	163	40.4	184	1270	924	166	183	27
CV 291/395596	F	193	63.6	293	—	1847	340	323	21
CV 292/395597	M	189	75.8	289	2275	1704	354	380	50
CV 293/395598	M	200	62.2	274	2129	1281	291	316	65
CV 295/395526	F	139	29.1	152	994	528	91	104	19
CV 296/395527	M	129	23.6	—	907	517	86	91	33
CV 297/395528	F	143	26.8	129	824	470	88	100	30
CV 298/395529	M	154	40.4	210	1323	1124	155	189	47
CV 300/395530	M	144	31.8	169	1019	647	114	121	38
CV 303/395532	M	143	29.5	141	1075	532	112	113	34
CV 304/395535	M	86	6.8	52	382	135	35	35	6
CV 305/395458	F	78	5.0	40	185	109	28	27	1
CV 306/395459	M	91	7.2	54	264	122	40	—	6
CV 307/395460	F	80	5.5	43	254	122	32	35	6
CV 308/395461	F	79	5.5	38	232	101	27	30	5
CV 309/395466	F	188	56.7	236	2078	1798	281	330	26
CV 310/395463	M	180	58.2	264	1642	1360	220	241	48
CV 311/395464	M	200	69.9	286	2090	1869	389	406	47
CV 312/395465	F	164	44.1	211	1317	1087	233	198	42
CV 313/395462	M	160	41.8	182	1291	999	177	179	62
CV 314/395467	F	184	55.4	284	1789	1600	284	290	20
CV 315/395468	M	162	43.6	227	1354	1139	193	190	35

TABLE 2. (Continued)

Specimen (field no.)/U. S. Nat. Mus. No. (skeleton)	Sex	Total length (cm)	Total weight (kg)	Heart (gm)	Lungs (gm)	Liver (gm)	Kidneys		Spleen (gm)
							Left (gm)	Right (gm)	
CV 316/395603	M	168	45.0	211	1457	1013	187	209	60
CV 317/395604	M	138	25.9	147	887	614	121	117	34
CV 318/395605	F	144	29.6	160	1047	684	115	114	39
CV 319/395606	F	168	46.8	204	1681	974	200	222	72
CV 320/395607	M	167	46.3	210	1672	1132	205	217	76
CV 321/395608	M	153	34.6	175	1304	774	130	140	34
CV 322/395609	F	142	26.3	119	853	528	102	110	26
CV 323/395610	M	162	46.8	201	1700	1076	191	190	33
CV 324/395611	F	136	25.4	126	959	523	82	94	11
CV 325/395612	M	135	29.5	153	1090	608	94	108	43
CV 326/395613 ¹	M	86	6.6	42	246	104	33	31	3
CV 327/395614 ²	F	81	5.9	44	245	84	29	30	3
CV 328/395615 ³	M	74	3.4	29	156	62	21	28	2
CV 329/395616 ⁴	F	81	5.7	—	—	—	26	26	4
PQ 01/395617	M	198	—	301	—	1234	231	247	42
PQ 02/395618	M	170	—	170	—	657	161	149	27
PQ 04/395410	F	168	—	219	—	995	197	176	27
<i>Stenella cf. S. longirostris</i>									
CV 285/395369	F	177	44.5	230	—	936	150	158	15
CV 288/395593	F	173	43.5	220	—	832	(—300—)		23
CV 294/395526	F	149	33.6	204	1112	855	116	137	43
CV 299/395531	M	119	18.6	114	631	368	58	69	14
CV 301/395533	F	140	26.3	135	812	542	73	88	16
CV 302/395534	M	118	18.1	97	599	367	60	63	29
PQ 03/395409	F	157	39.5	225	—	832	128	128	22
PQ 05/395411	F	168	46.7	196	—	971	147	164	13
PQ 06/395412 [†]	F	173	51.3	245	—	776	125	136	21
PQ 07/395413	F	176	52.2	191	—	871	145	144	—
PQ 08/395414	M	173	50.3	240	—	972	152	147	20
PQ 09/395599	M	173	59.0	272	—	997	192	201	31
PQ 10/395600	F	109	18.1	97	—	323	55	58	22
PQ 11/395601	F	105	13.2	72	—	282	46	51	10

[†] Individual was pregnant.¹ Fetus from CV 270/395336.² Fetus from CV 268/395333.³ Fetus from CV 272/395338.⁴ Fetus from CV 284/395395.

were weighed on platform scales, accurate to the nearest pound. The weights were converted to kilogram equivalents for use here. Some dehydration may have taken place during the storage periods, which ranged from 5 days to 14 months. When each specimen was dissected, the heart, lungs, liver, kidneys, and spleen were excised, placed in plastic bags, and refrozen. The sample size is not the same for all the organs, as these data were gathered incidentally to the primary purposes of the dissections, and some organs were not removed when time was short for other procedures. Later, the organs were thawed and weighed on a beam balance, accurate to the nearest

gram. Four of the female specimens of *S. graffmani* collected on April 9, 1958 were gravid with near-term fetuses, and the organs of these fetuses were included in the sample. Degree of sexual development was determined by histological examination of gonads. Complete skeletons of all the specimens are in the U. S. National Museum, Washington, D. C., and museum numbers are given in table 2.

The taxonomy of the spotted and spinner porpoises is confused (Perrin and Hunter, 1972), and the use here of *Stenella graffmani* and *S. longirostris* is provisional pending the results of studies underway by Perrin and others.

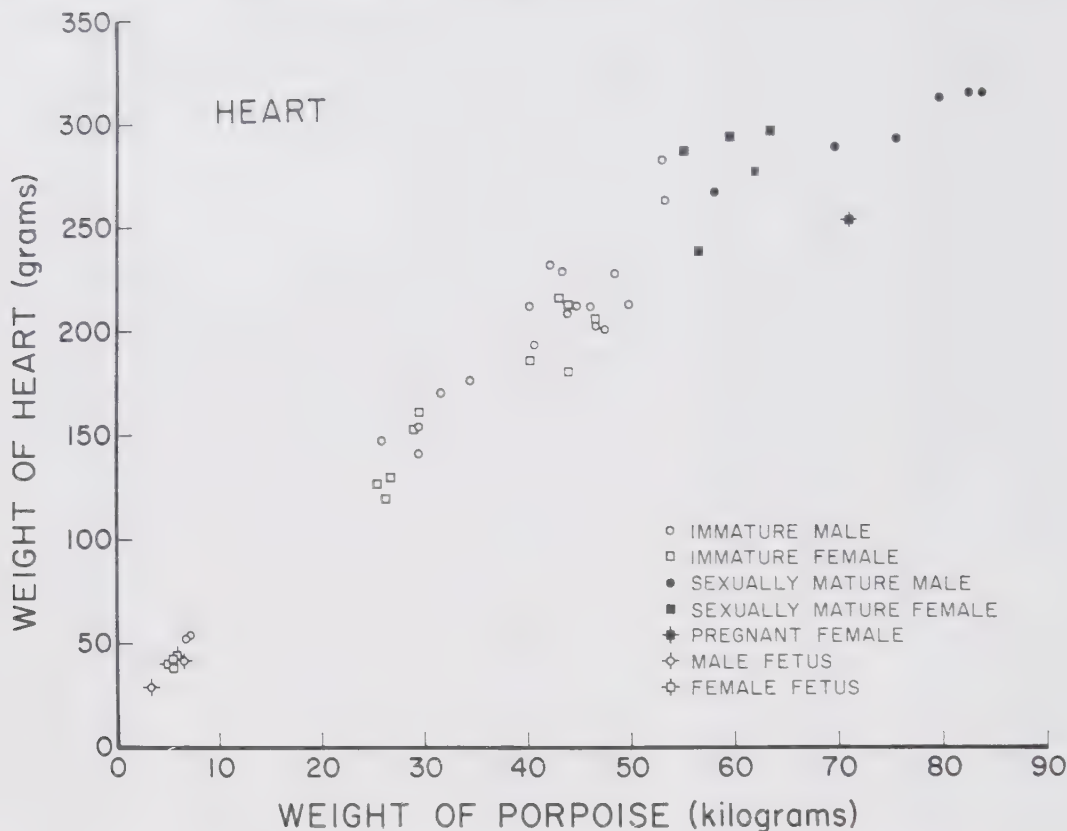


Figure 1. *Stenella graffmani*. Weight of heart relative to total body weight for 29 males and 19 females.

RESULTS

Heart

The data are presented in table 2. Scatter plots of organ weight on total weight are presented in figures 1-6 and 8-10. Where sample sizes were adequately large, the data were fitted to the equation $\text{Log } Y = a + b \text{ Log } X$ by the least squares method, where Y = organ weight in grams, X = total weight in grams, and b = Huxley's (1932) "growth coefficient" α . For the cases where correlation was statistically significant (at $P = 0.05$), the estimates of a and b are presented in table 3. Data for the pregnant females were not included in the regression analyses.

S. graffmani (Fig. 1). The hearts of 11 sexually mature adults (ranging from 180-218 cm total length and from 55.5-84.0 kg) weighed from 236-311 gm and from 0.37-0.51% (average: 0.43%) of total body weight. As is evident in figure 1, the relative weight of the heart decreases during development; the average relative weight for 28 calves and sexually immature subadults (ranging from 126-178 cm total length and from 25.4-53.6 kg total weight) was 0.48% (range: 0.41-0.57%) and for 8 infants and fetuses was 0.75% (range: 0.63-0.86%).

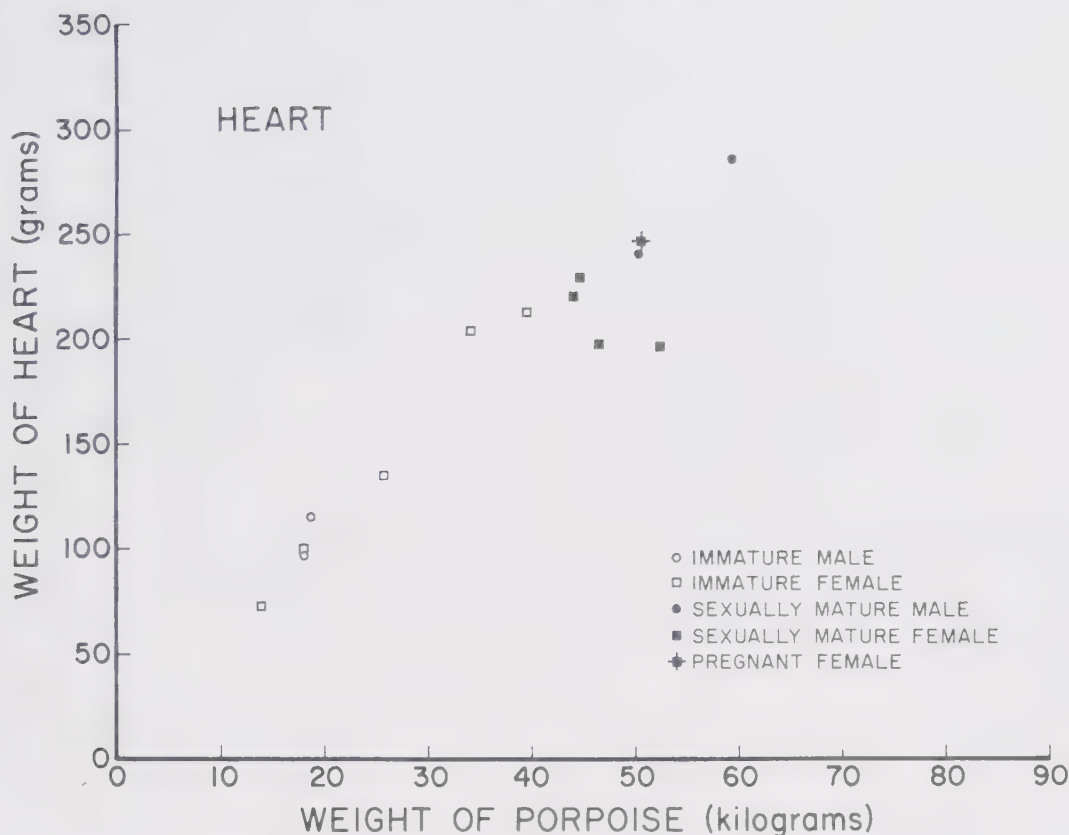


Figure 2. *Stenella cf. S. longirostris*. Weight of heart relative to total body weight for 4 males and 10 females.

TABLE 3. Log-log regression analyses of relationships between organ weights and total body weight in *S. graffmani* and *S. cf. S. longirostris*.

	a ¹	b ¹	r ¹	Sample size
<i>S. graffmani</i>				
Heart	-1.25	0.769	0.948	47
Lungs	-0.92	0.880	0.990	35
Liver	-2.18	1.114	0.922	59
Kidneys	-1.87	0.965	0.977	57
Spleen:				
males	-3.07	1.010	0.874	36
females	-3.40	1.057	0.885	24
<i>S. cf. S. longirostris</i>				
Heart	-1.48	0.820	0.962	13
Lungs	-1.25	0.947	0.991	4
Liver	0.01	0.608	0.536	13
Kidneys	-1.91	0.940	0.986	13

¹ Values of a, b, and correlation coefficient r in linear regression equation $\text{Log } Y = a + b \text{ Log } X$, where Y = organ weight and X = total body weight, in gms.

S. longirostris (Fig. 2). The hearts of 6 sexually mature adults (ranging from 168–177 cm total length and from 43.5–59.0 kg total weight) weighed from 191–272 gm and from 0.37–0.52% (average: 0.46%) of total body weight. The data are insufficient to determine whether relative weight of the heart decreases during development in this species.

Lungs

S. graffmani (Fig. 3). The combined weight of both lungs of 6 adults (from 180–200 cm total length and from 55.4–75.8 kg total weight) ranged from 1642–2275 gm and from 2.82–3.66% (average: 3.19%) of total weight.

S. longirostris (Fig. 3). The lungs of 4 individuals, all calves and subadults (from 118–149 cm total length and from 18.1–33.6 kg total weight) weighed from 599–1112 gm and from 3.09–3.39% (average: 3.28%) of total weight.

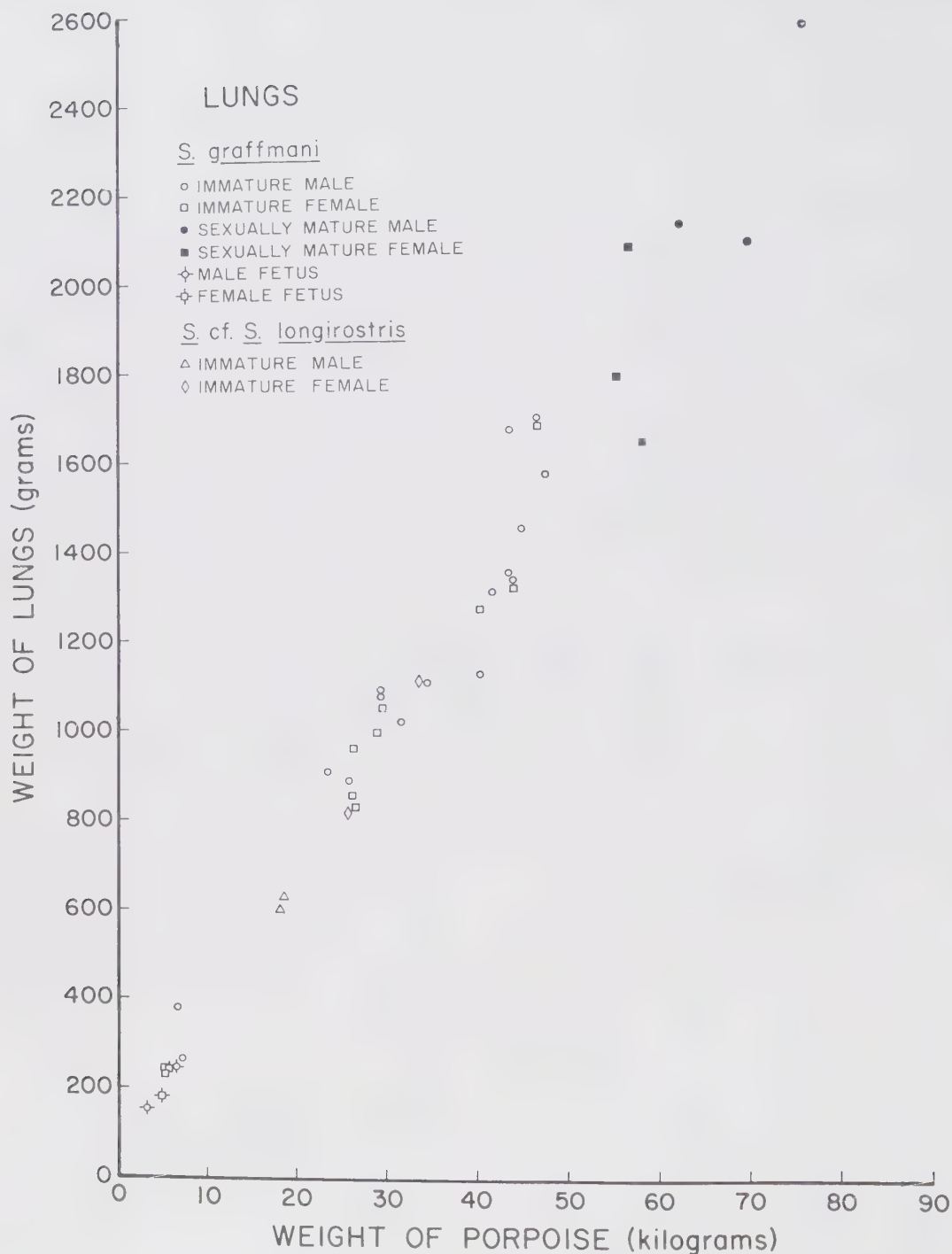


Figure 3. *Stenella graffmani*. Weight of lungs relative to total body weight for 22 males and 15 females. *Stenella cf. S. longirostris*. Weight of lungs relative to total body weight for 2 males and 2 females.

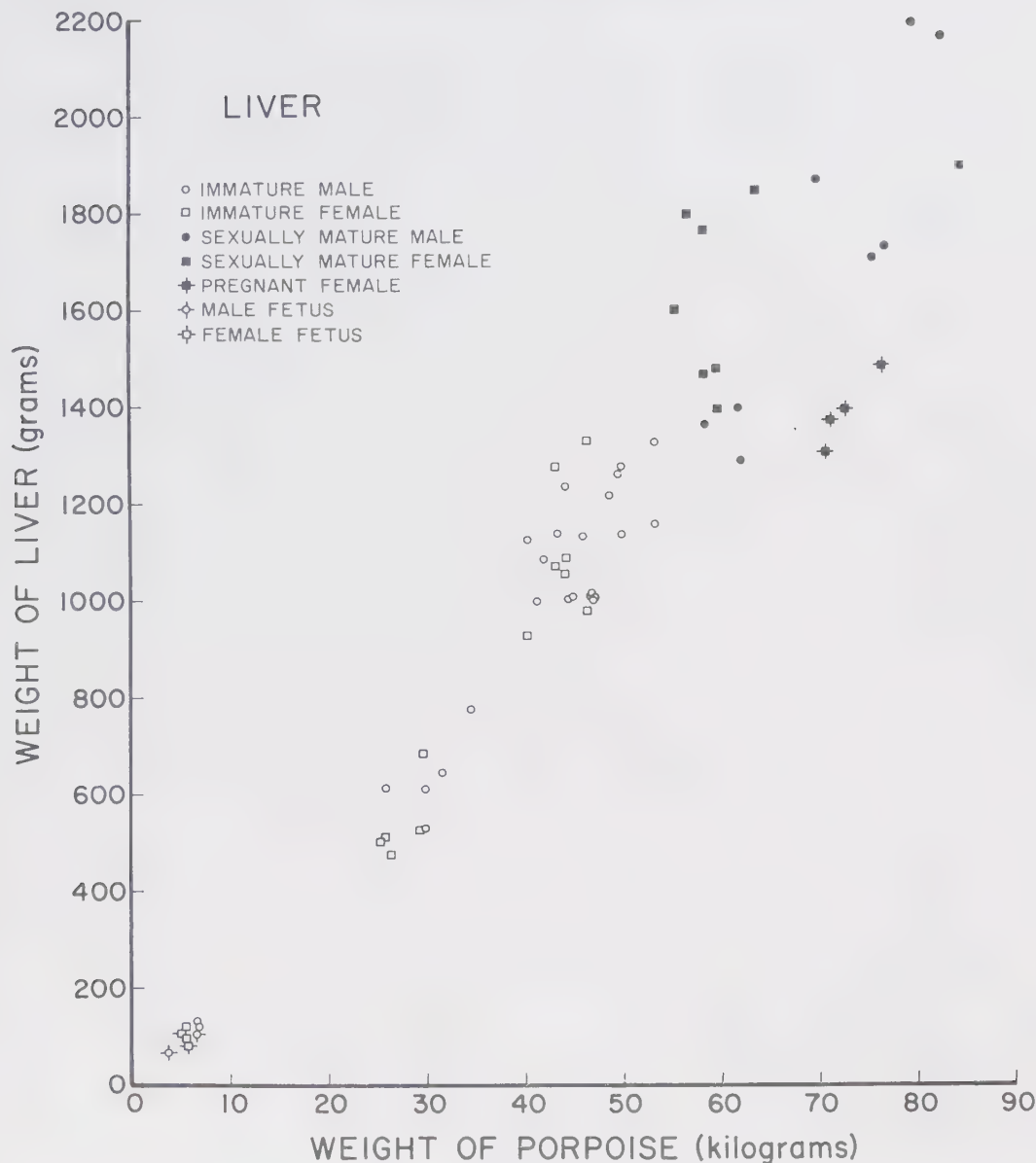


Figure 4. *Stenella graffmani*. Weight of liver in 36 males and 27 females.

Liver

S. graffmani (Fig. 4). The livers of 16 adults (from 175–218 cm total length and from 55.4–84.0 kg total weight) weighed from 1281–2195 gm and from 2.06–3.17% (average: 2.53%) of total weight. Relative weight of the liver appears

to increase early in development (average for 8 fetuses and infants was 1.84%, range: 1.42–2.22%) and remain nearly constant thereafter.

S. longirostris (Fig. 5). The livers of 6 adults (168–177 cm total length and 43.5–59.0 kg total weight) weighed from 832–997 gm and from 1.67–2.10% (average: 1.90%) of total weight. Adults

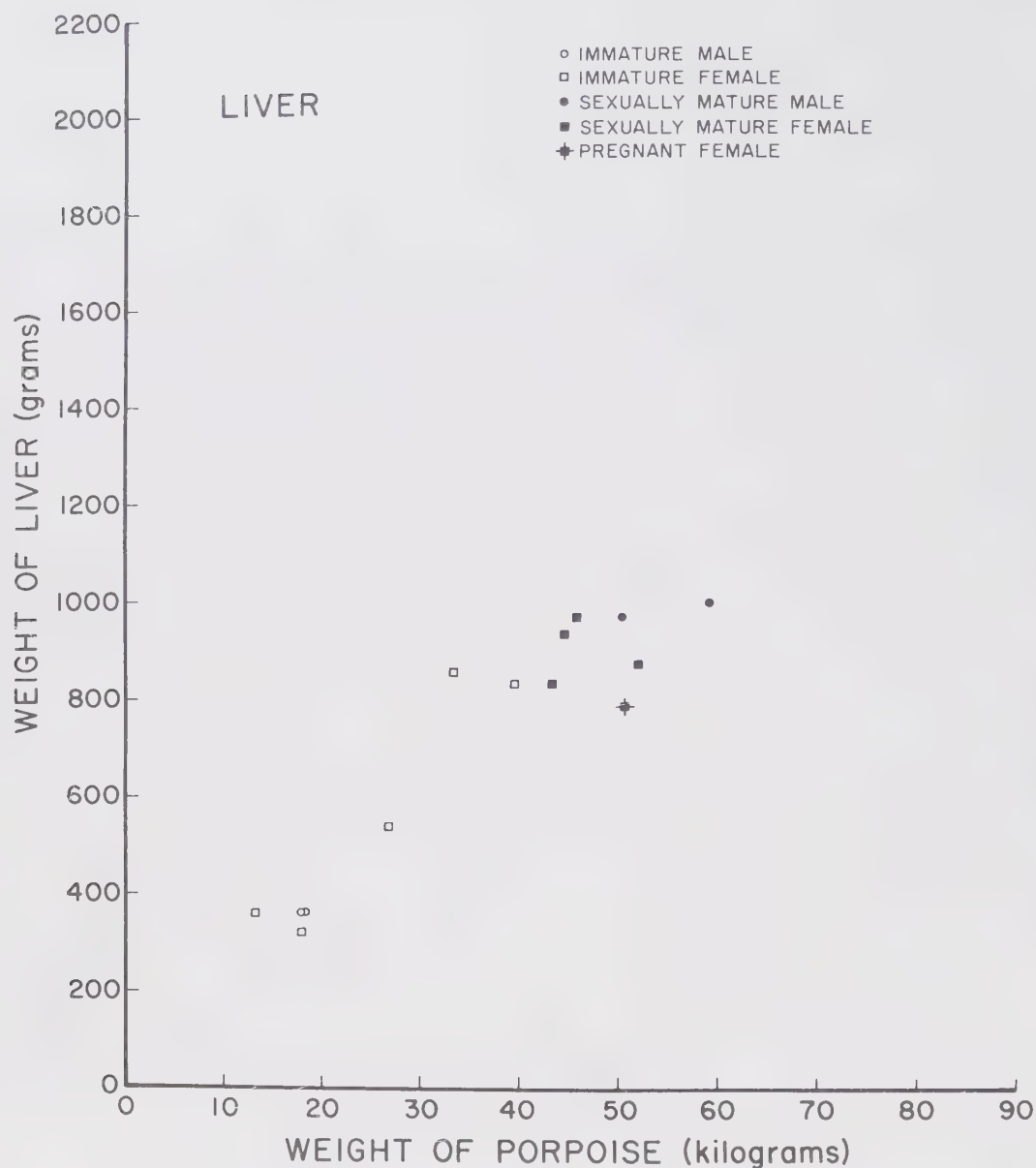


Figure 5. *Stenella* cf. *S. longirostris*. Weight of liver relative to total body weight for 4 males and 10 females.

of this species have smaller livers than subadults of *S. graffmani*; the livers of 21 calves and subadults of *S. graffmani* ranging from 43.2–53.6 kg total weight weighed from 974–1457 gm and from 2.08–3.00% (average: 2.42%) of total weight.

Kidneys

S. graffmani (Fig. 6). The relative weight of the kidneys drops from a high at birth to a low in calves and subadults and then increases again to a secondary high in adults. The kidneys of 8

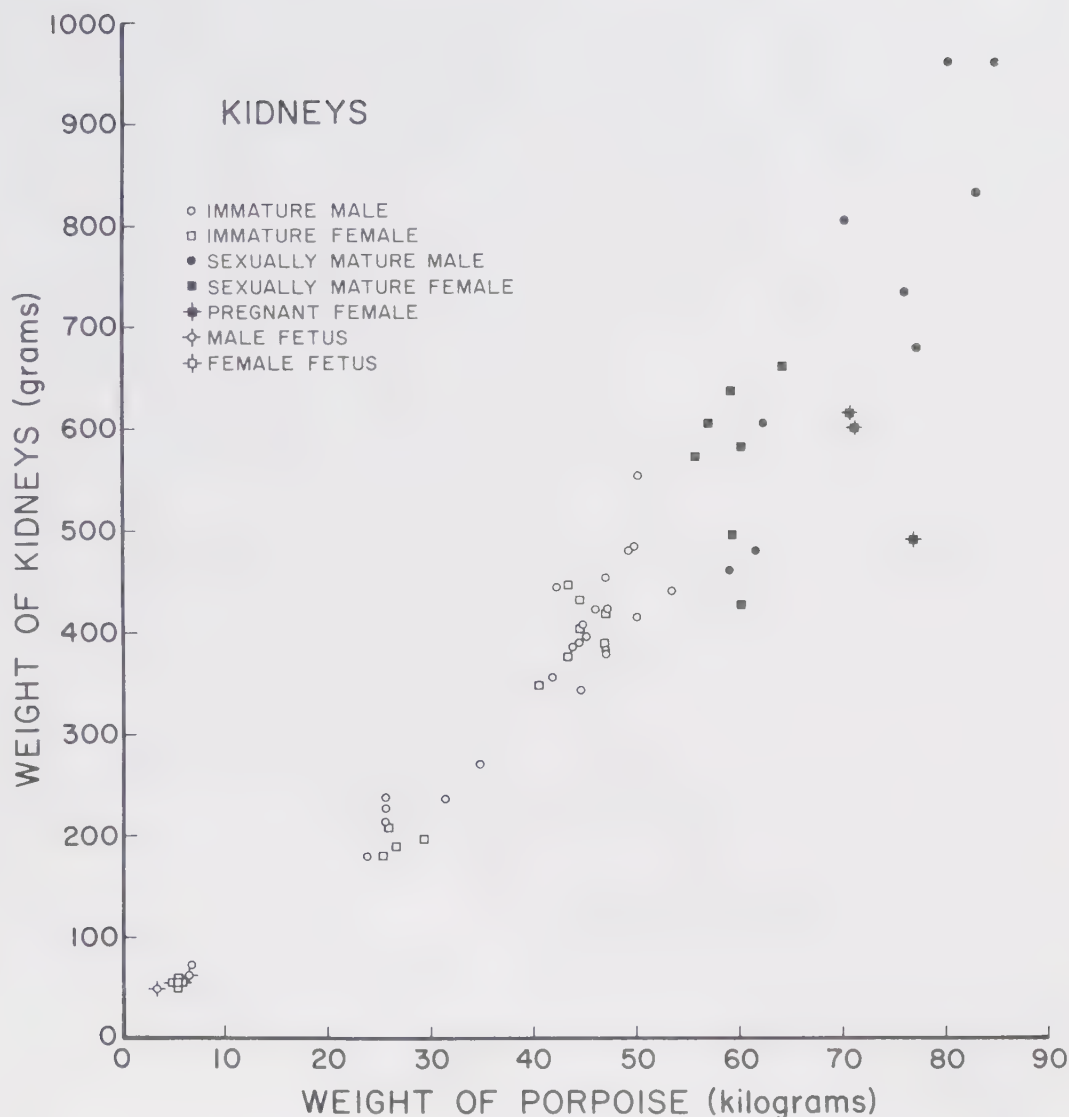


Figure 6. *Stenella graffmani*. Combined weight of kidneys relative to total body weight for 35 males and 27 females.

neonatal and near-term fetuses (74–86 cm total length and 3.4–6.8 kg total weight) ranged from 49–70 gm (average: 59 gm) and from 0.91–1.44% (average: 1.09%) of total weight. The kidneys of 31 calves and subadults (129–178 cm total length and 23.6–53.2 kg total weight) ranged

from 129–178 gm and from 0.67–1.11% (average: 0.84%) of total weight, and those of 15 adults (175–218 cm total length and 55.4–84.0 kg total weight) ranged from 426–968 gm and from 0.78–1.20% (average: 0.98%) of total weight. The animal is asymmetrical with respect to weight of

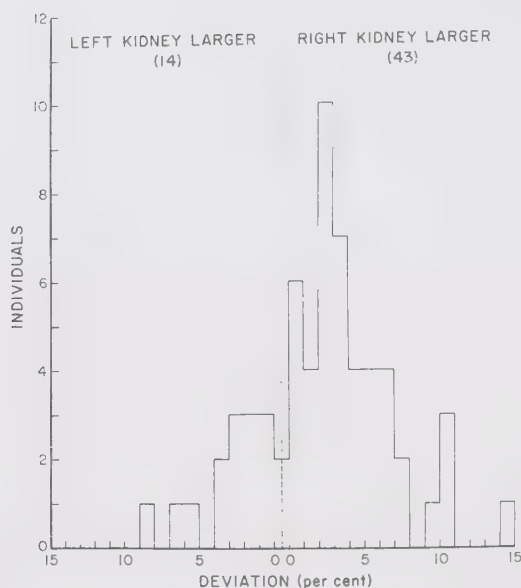


Figure 7. *Stenella graffmani*. Frequency distribution of percent deviation of weight of largest kidney from average weight of both kidneys, for 59 individuals.

kidneys (Fig. 7); the right kidney on the average is 2–4% heavier than would be expected were symmetry to prevail.

S. longirostris (Fig. 8). The kidneys of 6 adults (168–177 cm total length and 43.5–59.0 kg total weight) weighed from 289–393 gm and from 0.55–0.69% (average: 0.65%) of total weight. This species also exhibits dextral asymmetry; of 12 sets of kidneys weighed, in 9 the right kidney was heavier, in 2 the left was heavier, and in 1 set both kidneys weighed the same.

Spleen

S. graffmani (Fig. 9). We infer from the scatter plot of weight of spleen on total weight that the spleen increases in size both absolutely and relatively during development to a peak in subadulthood, then rapidly decreases in size, again both absolutely and relatively, to a relative low during adulthood. The spleens of 10 neonatals and near-term fetuses averaged 4 gm (0.07%) in weight, those of 11 calves (129–153 cm total length and 23.6–34.6 kg total weight) ranged from 11–43 gm (average: 31 gm) and from 0.04–0.15% (average: 0.11%) of total weight,

and those of 25 subadults (154–178 cm total length and 40.4–53.6 kg total weight) ranged from 24–100 gm (average: 53 gm) and from 0.05–0.21% (average: 0.12%) of total weight—the variance was greatest for this group, but the spleens of 16 adults (175–218 cm total length and 55.4–84.0 kg total weight) weighed only 20–65 gm (average: 41 gm) and from 0.03–0.10% (average: 0.06%) of total weight. There is also an apparent sexual dimorphism in weight of the spleen in adults; the spleens of 9 adult males weighed 36–65 gm (average: 48 gm) and 0.04–0.10% (average: 0.06%) of total weight, while those of 7 non-pregnant adult females weighed only 20–48 gm (average: 31 gm, the same as for the calves) and from 0.03–0.08% (average: 0.05%, less than for the infants and fetuses). The smallest adult spleen (16 gm or 0.02% of total weight) was possessed by a pregnant female (near-term).

S. longirostris (Fig. 10). As is the case for the liver and the kidneys, the adults of this species possess smaller spleens than do subadults of comparable size of *S. graffmani*. The spleens of 5 adults weighed 13–31 gm (average: 30 gm) and from 0.03–0.05% (average: 0.04%) of total weight. The data conform to the pattern noted above for *S. graffmani* of decreased absolute weight of spleen in adulthood but are insufficient in number to warrant conclusions.

DISCUSSION

The value of the growth coefficient *b*, the ratio of the rate of increase of organ weight to the rate of increase of total body weight, for heart weight obtained here for *S. graffmani* (0.769) is lower than those obtained by Pilleri (1969) for *S. coeruleoalba* (1.014), *Delphinus delphis* (0.806), and *Phocoena phocoena* (1.055). That of *S. longirostris* (0.820) falls between those for *D. delphis* and *S. coeruleoalba*. The value of the growth coefficient for lung weight appears to be inversely related to maximum body weight. Of the 3 species of *Stenella*, the smallest, *S. longirostris*, has the highest coefficient (0.947), and the largest, *S. coeruleoalba* has the lowest (0.684)—Pilleri, 1969. The value of *b* for *S. graffmani* is intermediate (0.880). The value of *b* for liver weight for *S. longirostris* (0.608) is close to that obtained for *S. coeruleoalba* (0.684) by Pilleri, but that for *S. graffmani* (1.114) is considerably

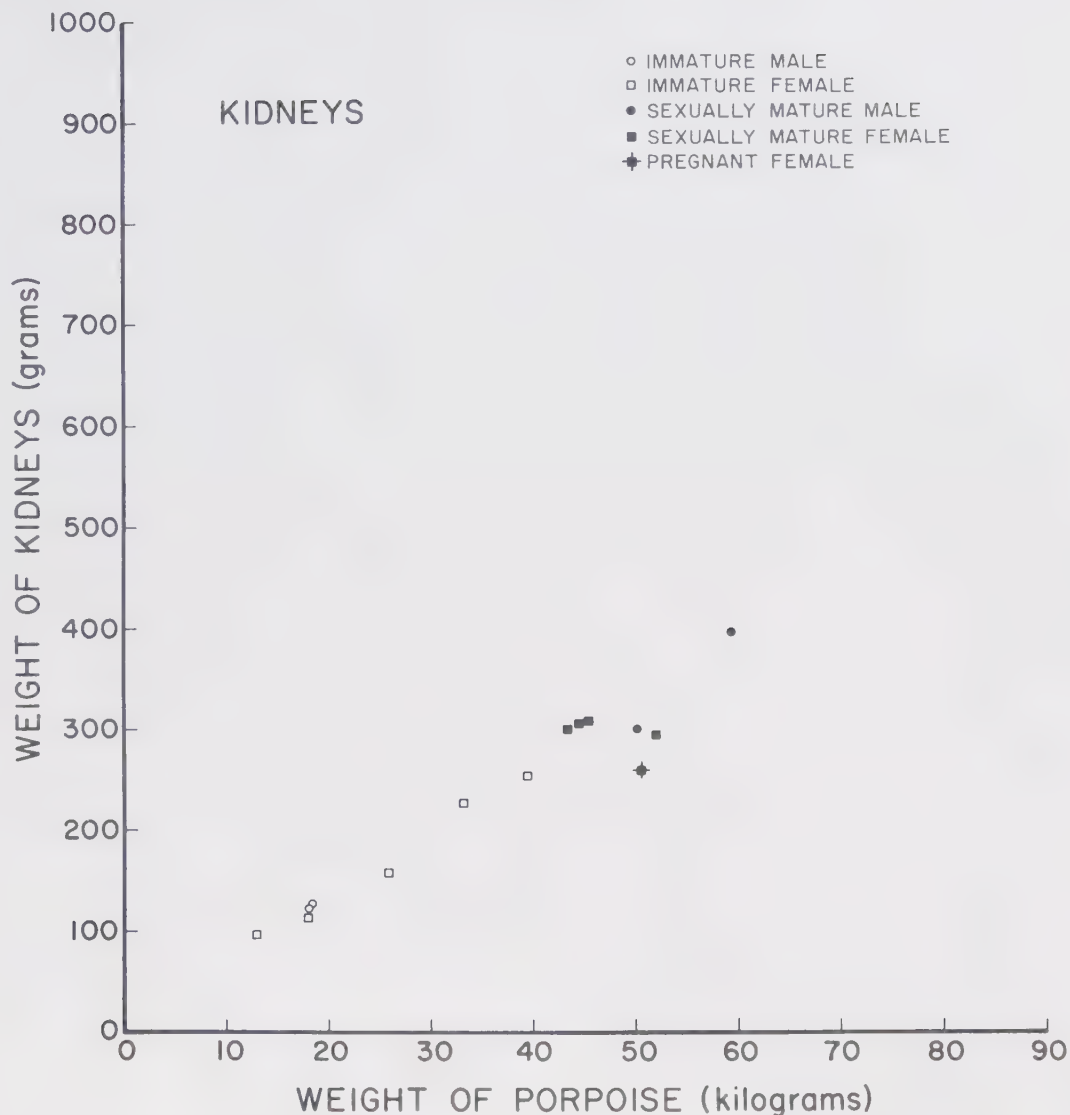


Figure 8. *Stenella* cf. *S. longirostris*. Weight of kidneys relative to total body weight for 4 males and 9 females.

higher. The values of b for kidney weight for both species dealt with here (0.965 and 0.940) are lower than those obtained by Pilleri for *S. coeruleoalba* (0.977) and *D. delphis* (1.089).

Pilleri's (1969) value of b for *Phocoena phocoena* (0.685) is very much lower than those for the 4 delphinids (*sensu stricto*).

The odontocete spleen has a relatively large

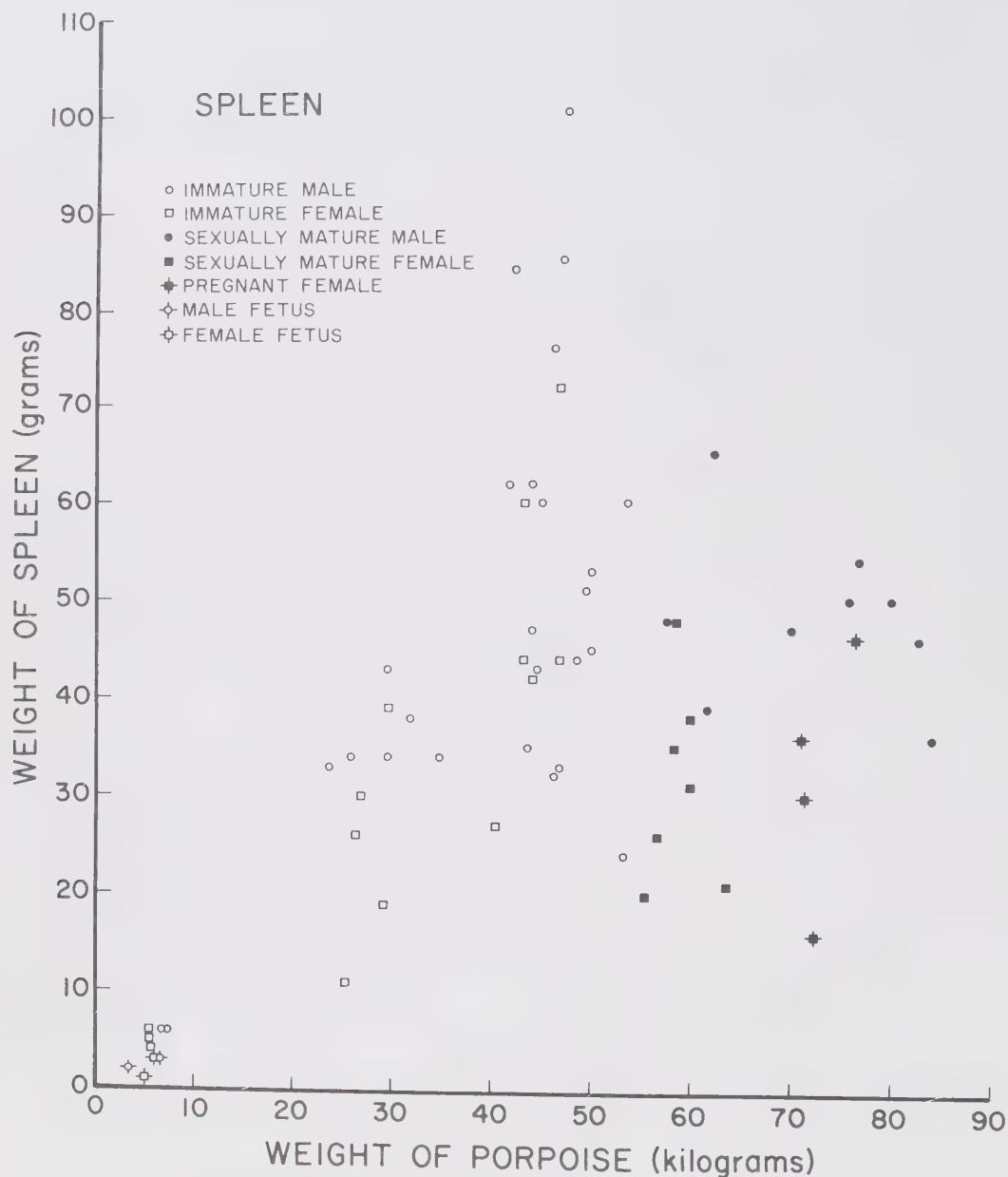


Figure 9. *Stenella graffmani*. Weight of spleen relative to total weight for 37 males and 28 females.

number of lymph nodules (white spleen pulp) (Filleri, 1969). A major function of the lymphatic tissue of the spleen is the production of antibodies (Jubb and Kennedy, 1963). We offer here the tentative hypothesis that smaller relative spleen size for adult females of *S. graffmani* (Fig. 8) is

tied functionally to suppression of antibody production during pregnancy to eliminate the possibility of rejection of the fetus. Obviously histological investigation of splenic change during pregnancy will be necessary if this hypothesis is to be critically examined.

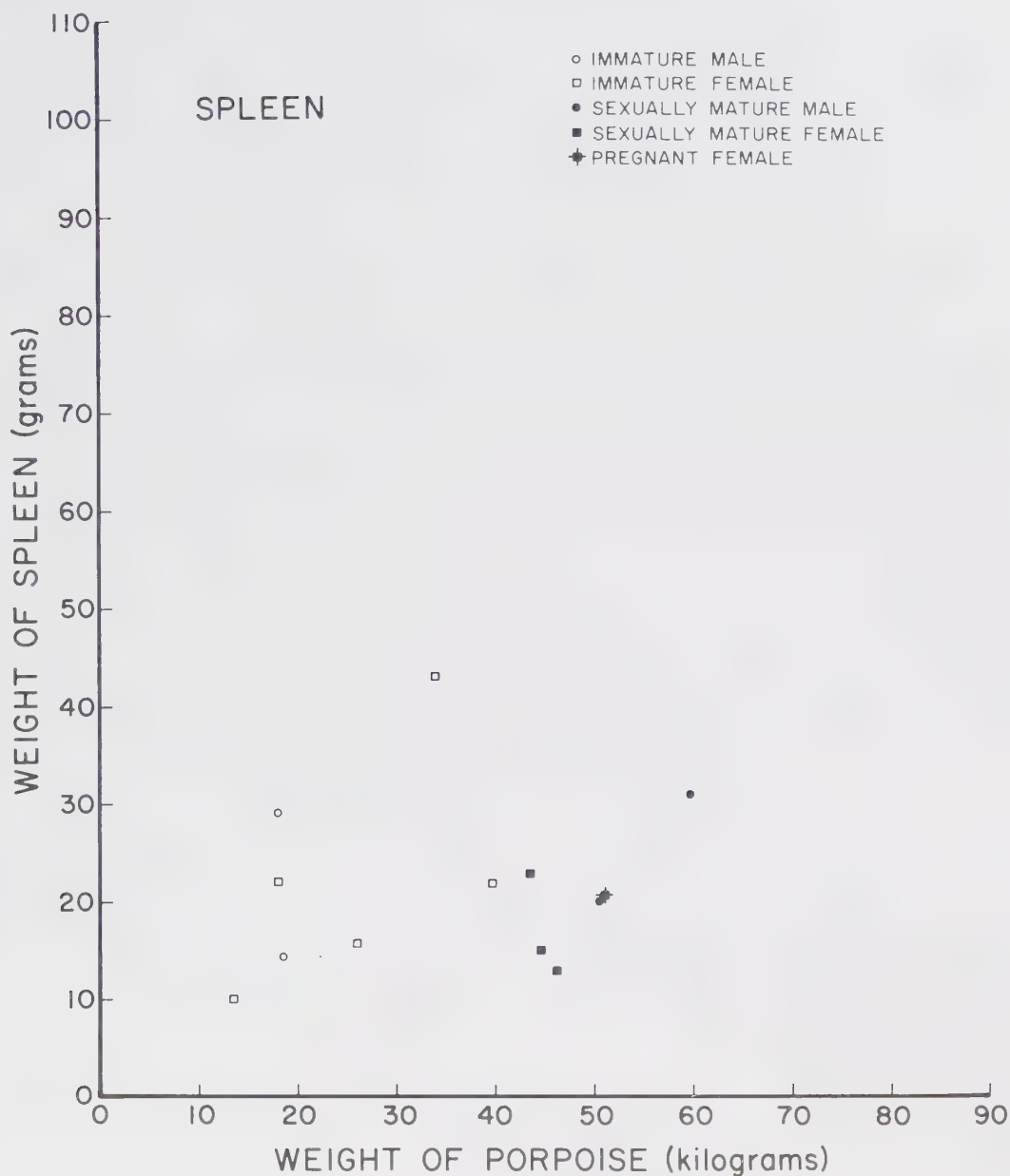


Figure 10. *Stenella* cf. *S. longirostris*. Weight of spleen relative to total weight for 4 males and 9 females.

ACKNOWLEDGMENTS

Specimens were collected through the cooperation of the owners, captains, and crews of M/V CAROL VIRGINIA and M/V PACIFIC QUEEN. Craig J. Orange and Susumu Kato helped secure the specimens. Support was provided by the National Marine Fish-

eries Service and the Inter-American Tropical Tuna Commission.

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Accepted for publication November 16, 1971.

ESCAPE BEHAVIOR OF THE HAWAIIAN SPINNER PORPOISE

*(Stenella cf. S. longirostris)*WILLIAM F. PERRIN AND JOHN R. HUNTER¹

ABSTRACT

Incidental mortality of porpoise (Cetacea, Delphinidae) occurs in the tropical tuna seine fishery. Experiments were carried out in a crowding chamber to determine behavioral responses of trained and naive Hawaiian spinner porpoise (*Stenella cf. S. longirostris*) to barriers of purse-seine netting, monofilament webbing, polyvinyl sheeting, rows of floats, and openings of various dimensions in a net wall. The object of the experiments was to generate information to be used in development of rescue gear and methods for the fishery. Openings of less than 1.5 m in width and/or 1 m in depth markedly inhibited escape. Negative effect of a line of floats across an opening at the surface was pronounced. Barriers of visually and acoustically relatively transparent monofilament webbing and polyvinyl sheeting were not apparently detected by porpoise prior to physical contact. Recommendations pertaining to potential design of rescue gear are presented.

Incidental mortality of porpoise occurs in the American purse-seine fishery for tropical tunas (Perrin, 1970). In 1970, the National Marine Fisheries Service began a program of research to develop improved gear and methods to reduce the porpoise mortality due to tuna seining. This paper reports the results of experiments on the responses to netting and other barriers by the Hawaiian spinner porpoise (*Stenella cf. S. longirostris*), a form closely related to one of the species involved in the tuna fishery.² We studied the response of the spinner porpoise to barriers of net, transparent monofilament nylon webbing, transparent polyvinyl sheeting, rows of floats,

and to openings of different dimensions in a net wall. The results of these studies will be applied in the design of an escape opening in the tuna purse seine. The experiments were carried out at Oceanic Institute, Oahu, Hawaii, in May, June, and July 1970.

METHODS AND MATERIALS

THE ANIMALS

Three of the five porpoise (Table 1) used in the experiments had been in captivity at Oceanic Institute and Sea Life Park for various lengths of time and are referred to below as the "trained porpoise"; the remaining two, referred to below

¹ National Marine Fisheries Service, Southwest Fisheries Center, La Jolla, CA 92037.

² Taxonomic note: The spinner porpoise of Hawaii has been variously referred to *Stenella longirostris* Gray 1828, by Nishiwaki (1967) and Tomich (1970), and to *S. roseiventris* Wagner 1846, by Fraser (in Morris and Mowbray, 1966) and Rice and Scheffer (1968). The spinner porpoise of the tuna grounds of the far eastern Pacific has been referred to *S. microps* Gray 1846 (Miller and Kellogg, 1955; Handley, in Hester, Hunter, and Whitney, 1963; Nishiwaki, 1967; Pilson and Waller, 1970) and to *S. longirostris* (Rice and Scheffer, 1968; Harrison, Boice, and Brownell, 1969). No critical review of the genus has been accomplished since True's work on the Delphinidae in 1889. The usage here of *S. longirostris* for the Hawaiian spinner is provisional pending the results of taxonomic studies underway at the Southwest Fisheries Center and elsewhere.

TABLE 1.—Hawaiian spinner porpoise (*Stenella cf. S. longirostris*) used in behavioral experiments.

Name	Date of capture	Sex	Weight at time of capture kg
Trained porpoise			
Waimea	Mar. 6, 1969	Male	50.0
Nani	Dec. 4, 1969	Female	59.2
Nohea	Dec. 4, 1969	Male	65.9
Naive porpoise			
Westward	June 11, 1970	Female	72.7
Moana	July 9, 1970	Female	51.3

as the "naive porpoise," were freshly captured, were not exposed to any training procedures prior to the experiments, and were tested immediately upon arrival at the Institute.

THE APPARATUS

The crowding chamber (Figure 1) was constructed in a large pool at the Oceanic Institute. The pool, known as "Bateson's Bay," is roughly circular, 24.7 m across at its greatest diameter, and approximately 4 m deep at its center. A smaller holding tank communicates with the pool through a wooden gate. Three hemispherical underwater viewing ports allow surveillance of the entire pool.

Net barriers were placed at various points along the pool wall to construct a circular enclosure or crowding chamber about 20 m in diameter in which porpoise were tested. The crowding chamber had two radial walls of netting that extended from the outer edge of the chamber to a central aluminum mast. One of the walls was stationary and was provided with escape openings of various dimensions. The other wall was movable and was used to drive the animals through the opening in the sta-

tionary wall. The movable wall pivoted on the central mast and was supported along the leading edge by an aluminum beam and on the distal end by a plastic float. The edge of the pool was marked at 1° intervals.

The walls were made of tuna purse-seine webbing ($4\frac{1}{4}$ -inch stretched mesh [10.8 cm] #42 thread knotted nylon). Flotation was provided by purse-seine-type corkline constructed of 6-inch diameter $\times$ $3\frac{1}{2}$ -inch (15×9 cm) sponge-plastic floats.

The basic escape opening was 18 ft (5.5 m) wide and 6 ft (1.8 m) deep. Flaps of purse-seine webbing were laced in, to variously decrease width to 10, 5, or $2\frac{1}{2}$ ft (approximately 3.0, 1.5, or 0.8 m) and/or depth to $3\frac{1}{2}$, 3, 2, 1, or $\frac{1}{2}$ ft (approximately 1.1, 0.9, 0.6, or 0.2 m). For tests of response to a barrier across the opening at the water surface, a corkline constructed of hollow plastic floats (5×9 inch [13×23 cm], 4 per m) was strung across the top of the opening. In tests of response to barriers of acoustically low-reflective materials, a panel of $3\frac{3}{8}$ -inch (stretched) mesh (8.6 cm) #12 monofilament webbing, a panel of 0.38-mm-thick polyvinyl sheeting, or a panel of 1.04-mm-thick polyvinyl sheeting, was laced into the opening.

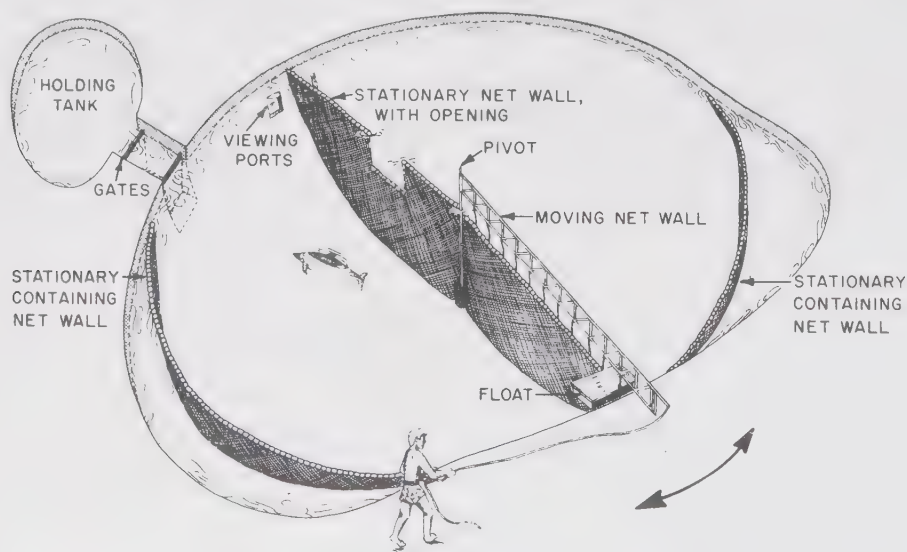


FIGURE 1.—Crowding chamber. Largest diameter of pool is 80 feet. Sketch not drawn to scale.

Acoustical tests carried out by the Naval Undersea Research and Development Center, San Diego, Calif., on plastic sheeting of similar thicknesses indicated effective acoustic transparency in the range of porpoise emanations (personal communication from W. E. Evans).

PROCEDURES

The moving wall was rotated around the center mast at a rate sufficient to completely close the chamber in about 4 min. An attempt was made to maintain a constant rate of rotation. Time required for an animal to escape from the chamber was recorded in seconds with a stopwatch, and position of the moving wall at time of escape was recorded in degrees. The reading in degrees was later used to calculate surface area remaining in the crowding chamber at time of escape. The wall was rotated alternately in clockwise and counterclockwise directions. After escape of an animal, the moving net wall was rotated until it was against the stationary wall, and the two radial nets remained together until the beginning of the next trial. Trails were spaced initially at 15-min intervals, to allow time for changing the escape opening. After our proficiency in altering the opening increased, the interval was decreased to 10 min.

Two major types of experimental design were

used: (1) a long series of trials alternating two treatments and (2) a series of blocks of consecutive trials of various treatments. In some experiments, the two approaches were combined to yield a factorial design testing simultaneously the effects of variation in two or three of the factors of width, depth, and presence or absence of corkline, monofilament, or polyvinyl barriers. In some tests of the monofilament and polyvinyl panels, the animal was subjected to a single trial with the panel after a series of learning trials without the panel or at the beginning or conclusion of an experiment involving other variables. The design of these experiments is referred to below as "single trial." The results of the first series of experiments (Waimea I, II, and III; see Table 2) using the alternating trials design indicated a probable influence by the direction of rotation of the net wall or by stage of practice effect. The small number of trials in each experiment precluded complete randomization, but the treatments in subsequent experiments were staggered to offset the effect of direction of rotation. A typical sequence of trials was: *a, b, a, b, a, b, a, b, b*; where *a* and *b* were different treatments, and rotation in the first trial was clockwise, in the second counterclockwise, and so on in alternating fashion. In this manner, an equal number of clockwise and counterclockwise trials was assured for each treatment.

TABLE 2.—Preliminary experiments with trained porpoise.

Porpoise	Experiment	Variables tested	Design	Number of trials
Waimea	I	Width	Alternating trials	20
	II	Width	Alternating trials	20
	III	Depth, corkline	Factorial	26
	IV	Monofilament panel	Single trial	14
Nani	I	Depth	Alternating trials	20
	II: trials 1-19	Width, depth	Factorial	19
	trial 20	Corkline	Single trial	1
	III: trial 1	Corkline	Single trial	1
	trials 2-16	Depth	Block	16
	trials 17-30	Depth, monofilament panel	Factorial	14
Nohea	I	Depth	Alternating trials	22
	II	Depth	Block	36
	III: trials 1-36	Width	Block	36
	trials 37-44	Depth	Alternating trials	8
	trial 45	Monofilament panel	Single trial	1
	IV	Width, depth, corkline	Factorial	32
	V: trials 1-8	Depth	Alternating trials	8
	trial 9	Thin polyvinyl panel	Single trial	1
	VI: trials 1-8	Depth	Alternating trials	8
	trial 9	Thick polyvinyl panel	Single trial	1

The remaining surface area between the advancing net wall and the stationary wall at the time of escape was used as a criterion of the animals' readiness to escape. This index was the inverse of latency, since the smaller the area that remained when the animal escaped the longer would be the latency. Although we measured latency in seconds, we felt the net position was the preferable measurement because the rate of net movement was imprecise, whereas the actual stimulus for escape, the reduction in the swimming area, could be measured relatively accurately. In presentation of the data, the logarithm (to base 10) of the remaining area at the time of escape is plotted on trial number.

Because procedures and plans were modified during the course of the experiments, results and interpretation are combined in the presentation of the results.

PRELIMINARY EXPERIMENTS WITH TRAINED PORPOISE

We anticipated that the behavior of the porpoise would change rapidly during the course of the experiments; thus, to avoid wastage of the naiveté of the limited and expensive supply of untrained animals, we conducted a series of preliminary experiments with three trained porpoise (Table 2, Figures 2-4).

WIDTH OF OPENING

The effect of the width of the opening on the escape behavior of the three trained porpoise was first tested by presenting on alternate trials an escape route of standard width, 5.5 m, and one either 3.1 or 3.8 m wide. In Waimea (Figures 2-I and II) and Nohea (Figure 4-IV) there was some evidence that the porpoise escaped sooner when the wider escape route was used but not in Nani (Figure 3-II). We felt this was probably an artifact of experimental design as described above and consequently we considered only the data from the block experiments for evaluating effects of width on the trained porpoise. To determine the width of opening that would influence performance, Nohea was tested over six

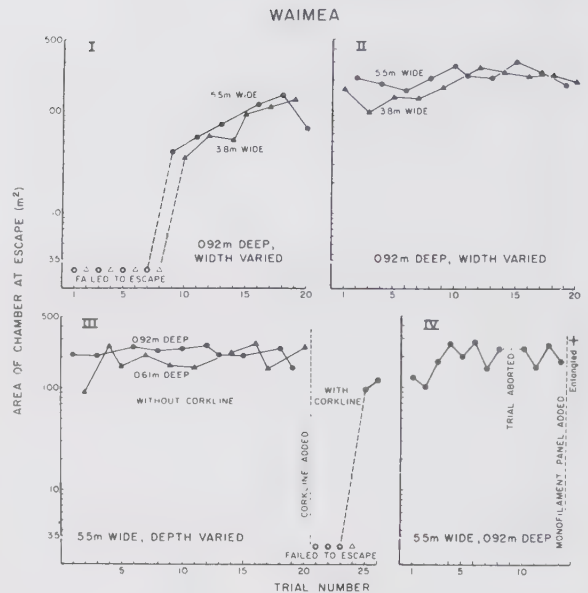


FIGURE 2.—Results of experiments with trained porpoise Waimea. Each plot summarizes one day's continuous experimentation, as follows: I. May 21, II. May 22, III. May 23, IV. May 25, 1970.

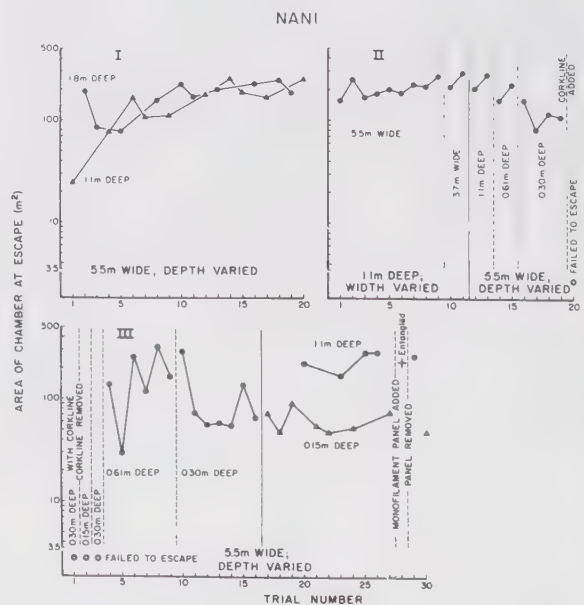


FIGURE 3.—Results of experiments with trained porpoise Nani. I. May 26, II. May 27, III. May 28, 1970.

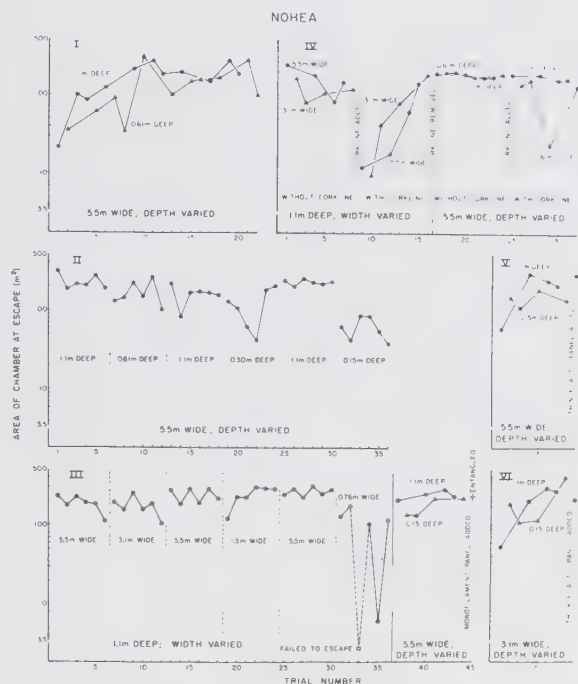


FIGURE 4.—Results of experiments with trained porpoise Nohea. I, May 30, II, May 31, III, June 1, IV, June 21, V, June 28, VI, June 29, 1970.

blocks of six trials each (Figure 4-III). The width of the escape route was 3.1 m in the second, 1.5 m in the fourth, and 0.76 m in the sixth block of experimental trials, with interspersed blocks of trials at 5.5 m. A significant decrease in performance occurred only when the escape opening was narrowed to 0.76 m. In one trial at 0.76 m the animal refused to leave the crowding chamber and had to be extricated from the webbing. In others, the porpoise exhaled air and sank passively to the bottom of the pool and did not move even when the chamber was completely closed. Exhalation of air and sinking to the bottom was a pattern that appeared in other porpoise in other experiments and was accompanied by failure to escape.

Our tentative conclusion was that the width of the opening was not a significant variable in the block experiments if it exceeded about 1.5 m.

DEPTH OF OPENING

We determined the effect of the depth of the escape route by varying depth of the hole from 1.8 m to 0.15 m while maintaining the standard hole width of 5.5 m. We will describe the results for each porpoise separately since the experiments were different for each animal.

Waimea failed in the first eight trials to escape through an opening 0.92 m deep (Figure 2-I). Performance improved thereafter to a plateau that was maintained throughout a subsequent identical experiment the next day, throughout a series of alternating trials with 0.92-m- and 0.61-m-deep openings on the third day of the experiments, and in a fourth experiment (Waimea IV) 2 days later with a 0.92-m-deep opening.

Nani showed no difference in response after the first two trials with openings 1.8 m and 1.1 m deep (Figure 3-I). High performance continued through a series of trials with a 1.1-m-deep opening, but dropped in blocks of trials of 0.61-m- and 0.30-m-deep openings (II). In subsequent experiments Nani failed to escape twice when openings 0.15 m and 0.30 m deep were used and performed erratically in blocks of trials with openings 0.61 m and 0.30 m deep (III). After seven trials with the 0.30-m opening, no failures was experienced in seven trials with a 0.15-m opening, but the animal escaped consistently earlier (larger remaining area) when the 1.1-m-deep opening was used.

Nohea escaped earlier when the hole was 1.1 m than when it was 0.61 m deep in 14 of the first 16 trials of an alternating series (Figure 4-I). In a subsequent series of blocks of trials at decreasing depths (II), a pronounced drop in performance occurred at depths of 1 ft and 5 ft. The following day's performance remained at a high level except when a corkline was strung across the opening (IV).

Our tentative interpretation of the above results was that a critical depth of opening lay near 1 m: 11 failures to escape occurred at 0.92 m or shallower; none occurred with openings 1.1 m deep or deeper; and performance was even more adversely affected by further decreasing the depth of the opening. We also concluded that the results of the first few trials for each ani-

mal were of most importance in predicting the probable response of naive wild porpoise, as the animals were able quickly to achieve high levels of performance even at very shallow depths.

CORKLINE

A corkline across the top of the opening caused Waimea (III) and Nani (II) to fail on initial trials, and greatly affected the performance of Nohea (IV). Waimea, after four failures, overcame reluctance to pass through an opening with a corkline at the surface and reached a high level of performance. An interaction between the corkline and depth of opening was apparent in the factorial experiment with Nohea. Initial trials with the corkline (second block) produced a temporary drop in performance with a 1.1-m-deep opening. In the fourth block, the corkline was again inserted, and performance dropped at 0.61 m depth but not at 1.1 m.

MONOFILAMENT PANEL

When the panel of nylon monofilament webbing was inserted into the opening (1.1 m deep) after a series of trials in which performance was consistently high, Waimea (IV), Nani (III), and Nohea (III) swam into the webbing as if it did not exist. Performance in subsequent trials without the panel was not affected (Nani III). Upon hitting the webbing, the porpoise became entangled and had to be extricated by a diver.

POLYVINYL PANEL

In the two single trials with a panel of clear polyvinyl sheeting inserted in the opening, Nohea (V and VI) hit the panel and slid over the top as it buckled. No difference was noted in behavior in these trials from that in trials in which the panel was absent.

During these experiments Nohea in several trials passed back and forth through the opening two or three times after the initial escape, while the net wall was being closed. The values for the surface area index shown in the figure are for the first passage. The incidence of such behavior throughout the course of all the experiments occurred only after considerable experience with a particular net configuration. In most cases, only one or two double "escapes" occurred during an experiment.

EXPERIMENTS WITH NAIVE PORPOISE

Eleven experiments were conducted with the naive porpoise (Table 3, Figures 5 and 6). The first naive animal, Westward, was captured on June 12, 1970, and after a relatively short handling period was placed in Bateson's Bay. Her swimming behavior during the first 5 days of captivity was unlike that of the trained porpoise. The trained porpoise continually swam about the tank during and between experiments, diving and "porpoising," and spinning. Westward, on

TABLE 3.—Experiments with naive porpoise.

Porpoise	Experiment	Variables tested	Design	Number of trials
Westward	I	Depth	Alternating trials	20
	II	Depth	Alternating trials	20
	III	Depth	Block	36
	IV: trials 1-40	Depth, width, corkline	Factorial	40
	trial 41	Monofilament panel	Single trial	41
	V	Width	Block	36
	VI: trials 1-10	Depth, thin polyvinyl panel	Factorial	10
Moana		trials 11-15	Block	5
	I	Depth	Alternating trials	11
	II	Depth	Alternating trials	20
	III	Width	Block	36
	IV	Depth	Block	24
	V: trials 1-12	Depth	Block	12
	trials 13-25	Width, corkline	Factorial	13

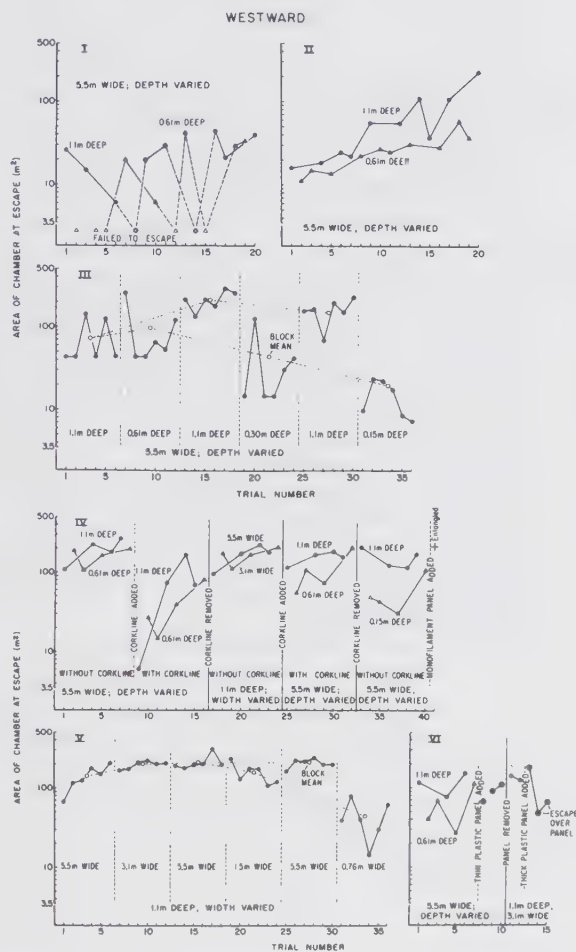


FIGURE 5.—Results of experiments with naive porpoise Westward. I. June 12, II. June 22, III. June 24, IV. June 25, V. June 26, VI. June 29, 1970.

the other hand, remained at the surface in a near-upright position with blowhole exposed and rostrum submerged, swimming very slowly with slow, low-amplitude beats of the posterior half of the body. Her head bobbed up and down slightly as she swam. Opinion among the animal-training staff of the Oceanic Institute as to the cause of this behavior was divided; some believed the animal to be in shock, perhaps even moribund, others believed the behavior to indicate extreme fright. The first experiment was

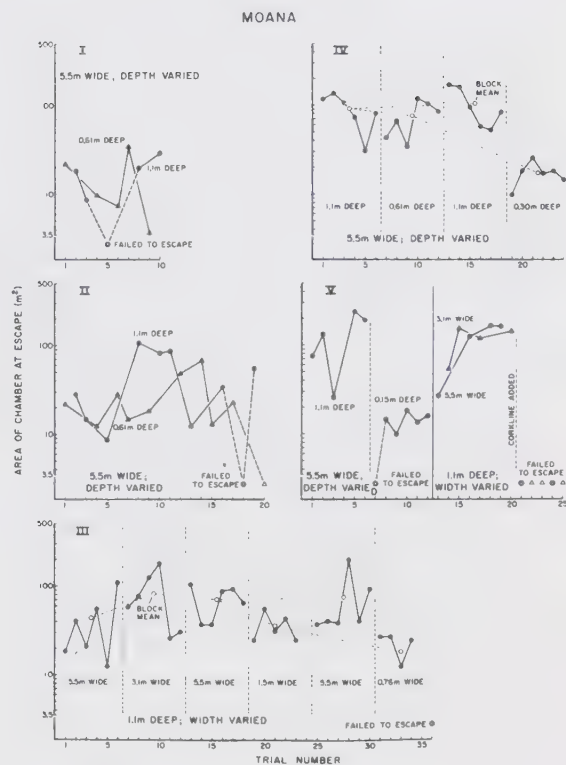


FIGURE 6.—Results of experiments with naive porpoise Moana. I. July 10, II. July 11, III. July 12, IV. July 13, V. July 15, 1970.

carried out the day after capture. Subsequently Westward's behavior slowly changed, until 5 days later on June 17 it was indistinguishable from that of the trained porpoise. The remainder of the Westward experiments were carried out after June 17.

Moana, the second naive porpoise, was captured on July 9, 1970. When placed in Bateson's Bay, she exhibited the same behavior as Westward, but to a lesser extent. Periods of surface swimming in a semiupright position, but without head-bobbing, were interspersed with periods of normal porpoising and diving. During the first experiment she swam slowly at the surface in the diagonal posture but during the second and subsequent experiments, her behavior was similar to that of the trained animals.

DEPTH OF OPENING

In the first few trials (Figure 5-I) a marked difference existed in the response of Westward to an opening 1.1 m deep and one 0.61 m deep. The animal swam slowly at the surface, circling or moving back and forth in the chamber. When the opening was 1.1 m deep, she moved slowly through the opening just as the moving wall closed. When the opening was 0.61 m deep, she moved past or circled slowly in front of the opening and then dove and entangled herself in the webbing of the moving wall. In the sixth trial, her behavior became more varied; she swam in tight circles beneath the surface and attempted to pass between the end of the moving wall and the periphery of the chamber before passing through the opening, after which she slapped her tail against the water surface. Behavior in subsequent trials became increasingly erratic. In trial 13 she darted through the opening rather than moving through slowly as in the previous trials. In trial 14, she tried again to squeeze past the moving wall and became lodged in the narrow opening. In trial 15, she assumed a position across the corkline of the moving wall, half in and half out of the chamber, and remained there until removed. In the remaining trials, she moved rapidly through the opening, and in the last two, she assumed a horizontal attitude similar to that usually taken by the trained porpoise and stopped bobbing her head but still kept her blowhole above the surface.

An identical experiment (II) of alternating trials was carried out 5 days later, after all traces of the slow surface-swimming and head-bobbing behavior had disappeared. Performance was consistently higher with the 1.1-m opening. The effect of depth is clearly seen in the results of a block-design experiment for Westward (III).

The second naive porpoise, Moana, a smaller and presumably younger animal than Westward, achieved a higher rate of successful passage in the first depth experiment (Figure 6-I). She failed only once, with the 1.1-m-deep opening. In the second depth experiment (II) her performance was extremely variable compared to that of Westward, and no relation between depth and success rate existed. In two trials (18 and

20) while swimming in tight circles near the apex of the chamber, she snagged her flipper in the webbing and had to be extricated. In later block-design experiments (V and IV) the effect of depth was evident as it was for Westward.

WIDTH OF OPENING

Results of block-design experiments testing the effect of width of opening for Westward (Figure 5-V) and for Moana (III) were similar to those for the trained porpoise (Nohea), but an effect was discernible at widths of 1.5 m.

As with the other experiments, performance of Westward was higher and more stable than that of Moana. Westward began to pass through the opening two or three times during a single trial. The frequency of multiple "escapes" was higher for the 5.5-m-wide opening than for the narrower openings (Table 4).

CORKLINE

Insertion of a corkline at the surface across the top of the opening sharply affected the performance of Westward (IV) and Moana (V). The performance of Moana showed the greatest effect. After a series of preparatory trials, Moana failed to pass through the opening in five straight trials with the corkline. In each trial she laid the anterior part of her body across the corkline and remained there until removed. In the block-design experiments with Westward (IV), the second block of trials with a corkline produced a smaller drop in performance than did the first, with the 0.61-m-deep opening only, demonstrating as for the trained porpoise (Nohea IV, Figure 4) an interaction between depth and presence or absence of a barrier at the surface.

TABLE 4.—Multiple escapes of Westward.

Width of opening in block of six trials	Number of double escapes	Number of triple escapes
m		
5.5	0	0
3.1	1	0
5.5	2	2
1.5	1	0
5.5	2	0
0.76	0	0

MONOFILAMENT AND POLYVINYL PANELS

When the monofilament panel was inserted into the 1.1-m-deep opening at the end of a series of depth trials, Westward (IV) "got up a full head of steam and plowed into the monofilament" (extracted from field notes of W. Wasden) and became entangled. Insertion of polyvinyl panels produced similar results in multiple trials; Westward (VI) in each trial hit the panel and slid over it and out of the chamber. There was nothing in the behavior of the porpoise to indicate that they recognized the presence of the panels.

DISCUSSION AND CONCLUSIONS

The swimming behavior of the naive porpoise Westward and, to a lesser extent, of Moana, the first few days after capture was very similar to that of porpoise (*Stenella* spp.) in tuna purse seines as observed by one of us (Perrin) off Central America. A typical "failure to escape" episode is illustrated for Moana in Figure 7. Immediately after a purse-seine net has been set, when the diameter of the encircled area is greatest (approximately 250 m), the porpoise swim about quite rapidly in small tight groups of a dozen or so individuals, the members of a group diving and surfacing together (Figure 8). As the net is hauled and the area enclosed becomes smaller, especially after the backing down operation (see Perrin, 1969), the porpoise congregate and raft near the center of the enclosure and mill very slowly, holding their bodies in a semiupright position with blowhole exposed and rostrum at or slightly below the surface (Figure 9). At this point, individual animals can be seen to leave the group and dive. When the net has been completely hauled, animals are often found with their snouts entangled in the webbing several meters below the corkline.

Although the head bobbing exhibited by Westward was not observed in the purse-seine situation, the similarities in behavior between freshly captured animals and those captured in a purse seine were striking. In both cases the animals did not display normal motor patterns;

they rested or swam at abnormally slow speeds, and this behavior was often ended by a rapid dive beneath the surface with no noticeable change in behavior preceding the act. The principal characteristics of this behavior, the inhibition of activity in a fear-inducing environment, resembled fear responses described for many other vertebrates and frequently classified as an immobility or freezing response (Ratner and Thompson, 1960; Hinde, 1970). Hogan (1965, 1966) suggested that withdrawal and immobility are separate, mutually inhibitory systems. If this view is correct, then driving porpoise through an escape route in the purse seine would not be successful once the animals began to show the immobility response, because withdrawal would be inhibited. Under these circumstances the additional fear stimulus associated with driving might be the catalyst for the rapid dive to escape, which results in entanglement. Driving may have to be carried out before immobility begins. Once the animals became immobile the only strategy may be to pull the net out from beneath them as is currently done during the "backing down operation" (Perrin, 1969).

That the behavior of Westward and Moana evolved into more typical behavior during the course of a single experiment also supports the notion that their unusual behavior was caused by the circumstance of captivity rather than ill health.

Our conclusions with respect to projected design of a rescue gate for removing porpoise from a purse seine during fishing operations were:

1. The gate should be sufficiently wide so that when the perimeter of the net circle buckles after pursing, the width does not become less than 1.5 m. Considering the equivocal results of the experiments for openings wider than 1.5 m, the opening should be as wide as practically possible.
2. Depth of the opening should be not less than 1 m and as deep as it is possible to make it without causing loss of the fish in the net.
3. There should be no line, corkline, or other barrier across the opening at the surface.
4. A self-actuating release port that will open when struck by a porpoise swimming into it



FIGURE 7.—Typical “failure to escape” episode. Moana (1) patrols moving wall at beginning of trial, then (2) takes up position at apex of chamber and remains there for most of trial, in vertical attitude. As chamber nears closure Moana dives (3), orients toward opening (4), and turns and swims into moving wall (5), becoming entangled (6).



FIGURE 8.—Porpoise (*Stenella graffmani*) in tuna purse seine at beginning of set, when net is at near-maximum diameter. Animals are circling and diving in groups of a dozen or so individuals.

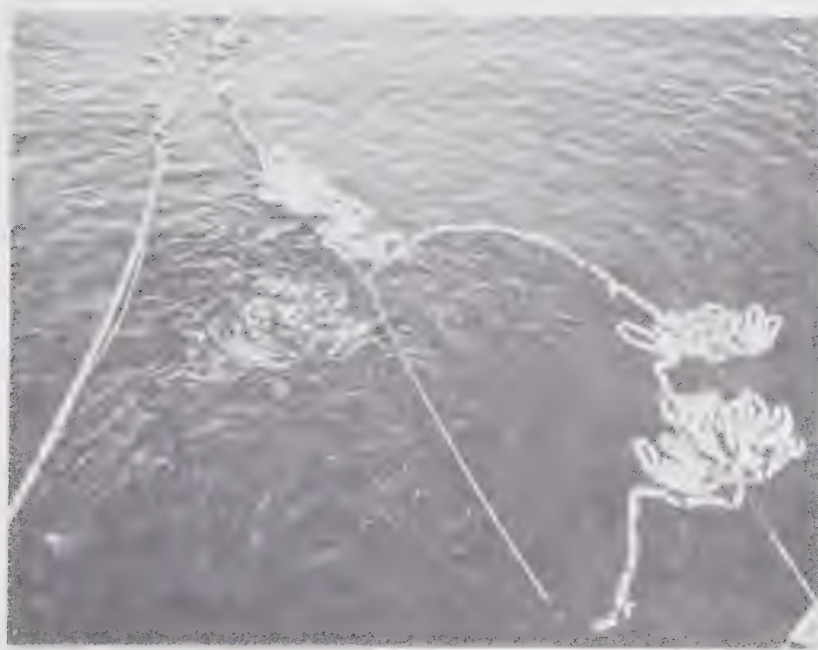


FIGURE 9.—Porpoise in purse seine, after most of net has been taken aboard. Animals are “rafting” in compact group, each maintaining approximately vertical attitude, with blowhole exposed and dorsal fin submerged. Large fish underwater in foreground are yellowfin tuna.

might be feasible if constructed of acoustically transparent materials, providing that it were so constructed that the fish in the net would not also use it.

5. It is to be expected that great difficulty will be encountered in inducing wild porpoise to pass through an opening in the perimeter of a purse-seine enclosure.

ACKNOWLEDGMENTS

We thank the Oceanic Institute and its Director, Dr. Kenneth Norris, for providing the facilities and the porpoise used in this study. William Wasden, National Marine Fisheries Service, Honolulu, Hawaii, assisted in all phases of the study, and porpoise trainers Ingrid Kang, Sea Life Park, and Scott Rutherford, Oceanic Institute, provided assistance and advice during the course of the experiments.

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FIRST RECORD OF THE GIANT SEADEVIL *Ceratias holbolli* FROM CALIFORNIA, BASED UPON A SPECIMEN FROM THE STOMACH OF A SPERM WHALE

A giant seadevil *Ceratias holbolli* Krøyer, 1845, the largest of the deep sea anglerfishes, was recovered from the stomach of a 13.0 m male sperm whale *Physeter catodon* that was killed on 13 November 1970, at lat. 37°50'N, long. 123°48'W (115 km west of San Francisco). This position is over the outer edge of the continental slope where the water is about 3,500m deep. The whale was taken by the catcher boat ALLEN CODY, Captain Douglas Campbell, of the Del Monte Fishing Company's whaling station in Richmond, California. Bernard Lenheim, then with the National Marine Fisheries Service (NMFS), examined the stomach of the whale (Field No. 1970-53). Elbert H. Ahlstrom of the NMFS, John E. Fitch of the California Department of Fish and Game, and Robert J. Lavenberg of the Museum of Natural History of Los Angeles County identified the anglerfish, which is deposited in the collection of the latter institute (LACM 31841-1).

Although the giant seadevil is virtually cosmopolitan, it has not previously been collected nearer to California than Cocos Island, the Galapagos Islands, the Hawaiian Islands, and Japan (Clarke, 1950). The few metamorphosed specimens that have been collected were caught at depths of 120 to 4390m, but most catches shallower than 600m were made in Arctic waters (Bertelsen, 1951; Clarke, 1950; Grey, 1956). The species was originally described by Krøyer (1845) on the basis of a specimen collected off Greenland.

This seadevil was the only one that I and my assistants found in the stomachs of 552 sperm whales taken off central California that we examined from 1959 through 1970. Sperm whales are deep divers (they are known to descend as deep as 1,134m) and feed mostly on large squids, but they also eat many large demersal and mesopelagic fishes. *Ceratias holbolli* has previously been reported from the stomachs of sperm whales taken in the Antarctic at lat. 61°S, long. 103°E (Clarke, 1950), off Western Australia (Bannister, 1970), near the Falkland Islands (Korabel'nikov, 1959), off South Africa (Penrith, 1967), and around the Azores (Clarke, 1956).

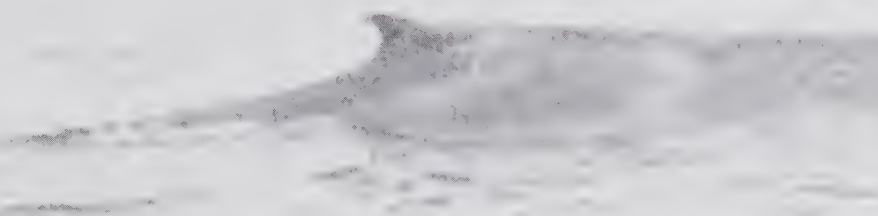
Although the specimen is partially digested, it is essentially entire and much of its skin is intact; the illicium is present, but the esca is missing. The total length of the fish is about 63cm excluding the caudal rays, which are missing. When whole, it

was probably about 75 or 80cm long. The maximum length reported for this species is 120cm (Bertelsen, 1951). The specimen is doubtless a female; the dwarf males of this species are parasitic on the females.

The vernacular name "giant seadevil" was suggested by Carl L. Hubbs, Scripps Institution of Oceanography, and will be used in a forthcoming check list of California fishes. In the spelling of the specific name and the date of its original publication, I have followed the advice of W. I. Follett, California Academy of Sciences.

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- Accepted for publication May 24, 1972.



"Ballena! Ballena azul!" I had almost dozed off in the warm sun on the flying bridge of the whale-catcher, *Lynnann*, when Ernesto's cry from the crow's nest jerked me to attention. Three miles off our port beam, a thin jet of vapor rose from the water, drifted downwind and dissipated. Then I spotted two great blue-green shadows gliding under the gentle swells. In a moment, they broke and sent up two more plumes of vapor. Ernesto repeated his cry — "Blue whales! Two — maybe three!" With a quick sighting over the compass binnacle, I kicked out the "iron mike" that had been holding us on course and spun the wheel to port. The *Lynnann* heeled hard over in a tight turn — a maneuver which brought the rest of the crew scurrying up from the galley. There is no whaler and no whale biologist, no matter how experienced, who is so jaded that his heart does not race at the sight of a blue whale.

Fifteen minutes of hard steaming brought us close to the whales. Captain Bud Newton took the wheel for the stalk. I positioned myself on the gun platform on the bow, but the big 90-millimeter harpoon cannon remained unloaded and covered. I was armed instead with a 12-gauge shotgun that fired 10-inch, pointed stainless steel tubes, each inscribed with a number and the message "Notify U.S. Fish and Wildlife Service." The next time the whales surfaced and blew, the skipper put us on collision course with them. A few minutes later, I spotted one of them in the clear water just ahead of us. Powerful rhythmic strokes of its 16-foot wide flukes effortlessly propelled its streamlined bulk through the water. After an eternity, the huge flat head broke the surface and the animal blew with a loud "whoosh" only 25 yards away. Braced on the pitching platform, I fired just as the whale arched its giant back to submerge. It did not even flinch as the mark buried itself into the back muscles — a mere mosquito-bite.

These blue whales which congregate off the coast of Baja California every year from February to June represent one of the last sizeable stocks of blue whales left on the earth. We do not know where they spend the remainder of the year; our reason for marking them was to trace their migration routes. If they should be killed on the whaling grounds farther north, the marks would be discovered in their flesh and we would be able to determine where they spent the summer. Unfortunately for science, but fortunately for the survival of the species, blue whale hunting was banned shortly after our marking program got under way, so their wanderings still remain a mystery. The marks should remain in them for life — which could be over 60 years — so the mystery may be solved decades hence, after the population has increased enough to justify whaling again.

At one time or another, blue whales have been found almost everywhere in the world's oceans, from the equator to 85° north latitude in the Arctic Ocean north of Spitzbergen, and to 78° south latitude in the Ross Sea of Antarctica. Their main summer feeding grounds, however, are restricted to relatively small areas

of the most highly productive waters.

most abundant in the circumpolar belt between the Antarctic pack ice and the Antarctic Convergence, which delimits the boundary between the cold Antarctic waters and the temperate waters at about 50° to 60° south latitude. A smaller variety called the pygmy blue whale inhabits the waters between 40° and 55° south latitude in the southern Indian Ocean, particularly around Marion Island, the Crozet Islands, and Kerguelen Island. During the austral winter, the Antarctic blue whales migrate to lower latitudes. At that season, they are found as far north as Ecuador, northeastern Brazil (rarely), Angola (and rarely to Gabon), Madagascar, and western Australia and New Zealand (infrequently). Blue whales have also been found in the Arabian Sea, the Bay of Bengal and the Java Sea, but it is not known whether these animals are from the Antarctic stock.

In the North Pacific, these giants range during the summer in the immediate offshore waters from central California and the northeastern coast of Hokkaido north to the Gulf of Alaska and the Aleutian chain. They rarely enter the Bering Sea but have on occasion been observed as far north as the Chukchi Sea. In winter and spring, they congregate off the west coast of Baja California — where I have observed them most often — and at least formerly from southwestern Honshu to Taiwan on the Asiatic side. At this season, a few have also been sighted in mid-Pacific between 20° and 35° north latitude.

The North Atlantic blue whales spend the summer from the Gulf of St. Lawrence north into Davis Strait as far as Disko Island on the west coast of Greenland and from southeastern Greenland, Iceland, the Faeroe Islands, Scotland and Ireland (and rarely Spain), north to northern Norway, Bear Island and Spitzbergen, and sometimes east to Novaya Zemlya. In winter they have been seen in the waters between west Africa and the Cape Verde Islands. No regular winter grounds have been discovered in the western North Atlantic, but in January, 1922, a blue whale swam up the Panama Canal as far as the Gatun Locks and had to be executed as a hazard to navigation!

The blue whale (*Balaenoptera musculus*) is the largest of the rorquals, a family of baleen (whalebone) whales characterized by their pleated or corrugated throats. The six species of rorquals range in size down to the little minke whale (*Balaenoptera acutorostrata*) which is only 30 feet long. Aside from its great size, the blue whale may be distinguished by its blue-gray color, mottled with lighter gray; only the undersides of its flippers are white. The dorsal fin is small — little more than a step in the ridge of its back — and its tongue, palate and baleen plates are inky black.

Although these are the largest animals that have ever lived, it is difficult to separate fact from fiction when you try to find out exactly how big they do get. After combing the literature



and questioning whale biologists from all over the world, I find that the longest blue whale (measured in the standard zoological manner in a straight line from the tip of the snout to the notch between the tail flukes) that can be authenticated was a 98-foot female examined by Dr. Masaharu Nishiwaki of the Japanese Whales Research Institute in the Antarctic in the 1946-47 season. The heaviest blue whale on record in an 89-foot female that was cut up and weighed piece by piece aboard a Japanese floating factory ship in the Antarctic on 27 January 1948 — she weighed 285,600 pounds. Allowing for a 12% loss of blood and body fluids, she must have weighed about 320,000 pounds when alive. The largest blue whale that I have examined in the North Pacific was an 82-foot female killed off San Francisco on 23 September 1959. This animal weighed 181,200 pounds and must have weighed about 203,000 pounds in life. She yielded 52,500 pounds of meat.

Blue whales become sexually mature when about ten years old. From that age onward, each female gives birth to a calf once every two or three years. The mating season extends over about five months in the late fall and winter and the gestation period lasts about a year. Since the annual cycles of Southern Hemisphere and Northern Hemisphere blue whales are six months out-of-phase, they cannot interbreed.

At birth the blue whale calf is about 23 feet long and weighs about 5,500 pounds. During the nursing period, its mother must supply over 50 gallons of milk a day. This milk contains 35 to 50% fat and enables the calf to gain weight at the prodigious rate of over 200 pounds a day or some nine pounds per hour. By the time it is weaned at the age of seven months, the calf is 52 feet long and weighs 50,000 pounds.

Of all the large whales, blue whales are the most particular about their diet. They are not known to feed on anything other than certain species of "krill" — small shrimp — like crustaceans belonging to the family *Euphausiidae*. The particular species they eat varies from one part of the world to another. In the Antarctic Ocean, it is *Euphausia superba*, a "giant" species that reaches a length of over two inches. Off California and in other parts of the North Pacific, the main species is *Euphausia pacifica*, which is less than an inch long; of secondary importance is a slightly larger species called *Thysanoessa spinifera*. In whatever part of the world, the species of krill selected by the blue whale all have two characteristics in common: they congregate in large, dense shoals and they live fairly close to the surface. The only possible exception to this exclusive diet of euphausiids is off Baja California; I have observed blue whales there that appeared to be feeding on "red crabs" (*Pleuronocodes planipes*) which look like tiny lobsters and — like the euphausiids — often gather in immense shoals at the surface.

An average blue whale weighing 75 or 80 tons probably requires about 1.5 million calories a day. Since it fasts for much of the winter, it must consume about twice this amount — or

three million calories a day — during the summer months. One pound of *Euphausia pacifica* supplies about 400 calories. This means that it must consume about four tons of krill every day. Its stomach holds about a ton, so it eats four full meals a day. Each individual of *Euphausia pacifica* weighs only one-tenth of a gram, so it takes about 40 million of these krill to sustain one blue whale for one day.

To obtain this immense quantity of food, a blue whale must filter thousands of cubic yards of water through the sieve-like series of baleen plates — about 325 on each side — which grow in its upper jaw. Most species of baleen whales fall into two groups on the basis of their feeding behavior: the "skimmers" — such as the right whale and the sei whale — that swim along with their mouths wide open, and the "gulpers" such as the blue whale. When a blue whale encounters a shoal of krill, it rolls on its side, presumably to allow more maneuverability in the horizontal plane. Its huge U-shaped lower mandible hangs open about 50 degrees and its pleated throat balloons out. Slowly it engulfs a mass of krill, closes its mouth and, by tightening its throat muscles, sends the water streaming out between its baleen plates, leaving the krill trapped on the fibrous fringes of the inner edges of the baleen plates. Its huge fleshy tongue then scrapes the krill back to the gullet. The whale repeats this process hour after hour, day after day.

Probably because of their fastidious diets, blue whales are much less prone to infestations of parasitic worms than are other species of baleen whales. In their stomachs, I have never found the herring-worms (*Anisakis simplex*) which other species of baleen whales often harbor in great numbers — apparently picked up by eating fishes infested with the immature stages. About half the blue whales taken off California carried thorny-headed worms (*Bolbosoma nipponicum*) attached to the lining of their small intestine. The only other internal parasite I have found was a giant kidney worm (*Crassicauda crassicauda*) in about one quarter of the animals examined.

Blue whales do not usually carry many ectoparasites either. The few they do have are among some of the most peculiar creatures in the animal kingdom. *Pennella* is a crustacean of the Order Copepoda — so highly specialized that at first glance it is not even recognizable as an animal. It grows anchored in the whale's blubber by a three-pronged tripod-shaped "root", between the "legs" of which is the rounded head; the stem-like "neck", which is several inches long, protrudes from the whale's skin and is terminated by a thickened "trunk" which bears a fringe of gill filaments and two long thread-like ovipositors. The male — rarely seen by zoologists — is a tiny creature that looks more like a normal crustacean. Another unique ectoparasite is a barnacle called *Xenobalanus globicipitis*. Although a true sessile barnacle, it looks more like one of the stalked or goose-neck barnacles, because the shell is reduced to a small star-shaped structure. Most of its body — which may be over two inches

long — protrudes from the shell; it is long and cone-shaped with a turned-down "collar" through which its *cirri*, or legs, are protruded. This barnacle selects as its habitat the trailing edge of the tail flukes and occasionally the tips of the flippers or dorsal fin. On one whale, I found several hundred forming a solid rank along the hind margin of the flukes. In such a position, they must withstand a terrific water velocity when the whale is swimming fast. The barnacles are not true parasites but filter their own food from the water flowing past the whale. Blue whales rarely carry "whale-lice" (really amphipod crustaceans) of a species (*Cyamus balaenopterae*) that also occurs on other species of rorquals.

Just as the barnacles "ride" the whale in order to take advantage of the food-carrying water currents, other fellow travelers have adapted themselves to exploit the tremendous volume of water that flows between the baleen plates. *Balaenophilus unisetus* is an almost microscopic copepod crustacean that lives in such uncountable millions on the baleen plates as to form a whitish scum. "Big fleas have little fleas. . .", and so *Balaenophilus* carries on its body and legs many jug-shaped ciliate protozoans belonging to a still-undescribed genus. Another denizen of the baleen plates is a tiny roundworm called *Odontobius ceti*.

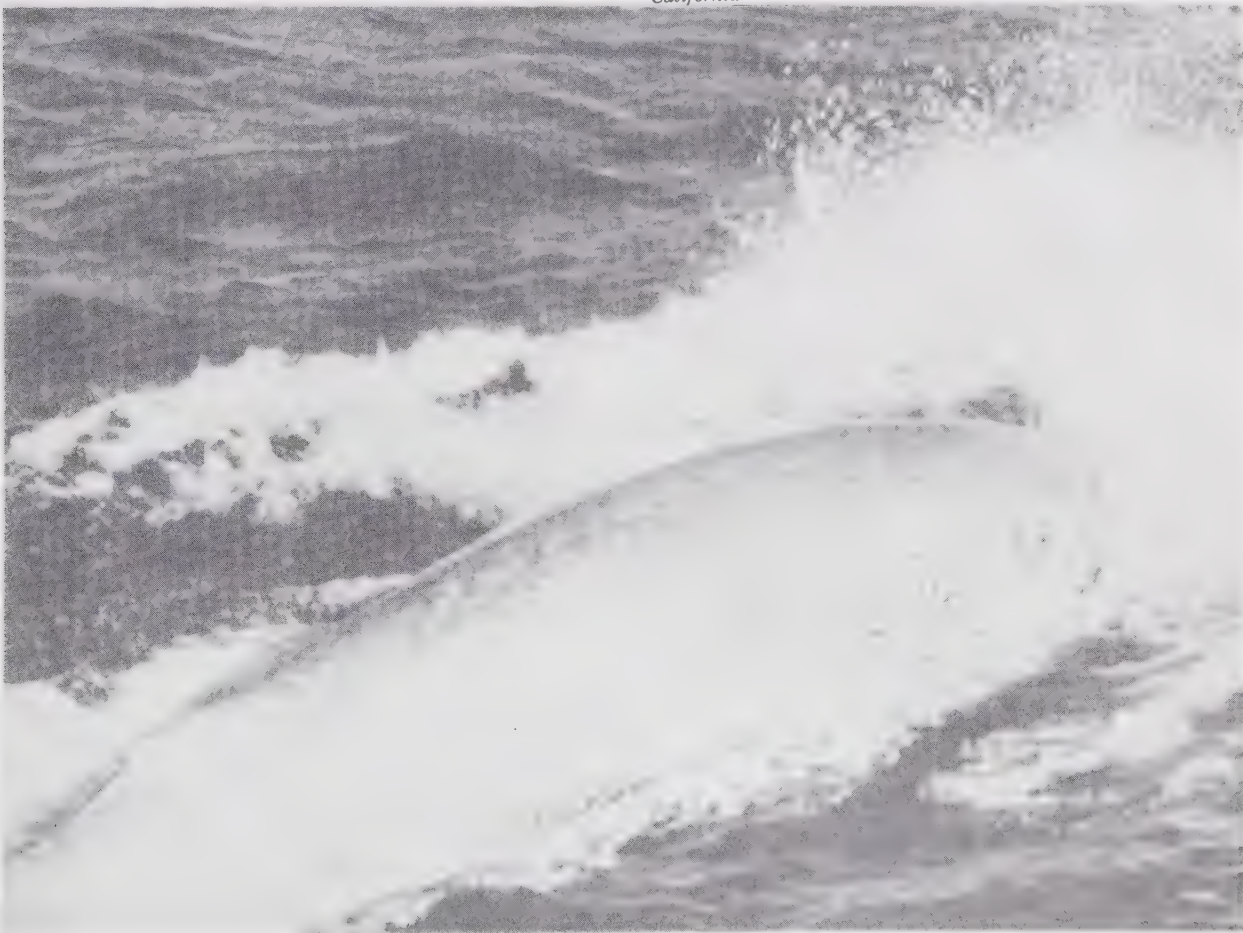
One of the most interesting creatures that makes the blue whale its home is the whalesucker (*Remora australis*), a fish related to the more familiar sharksucker. This fish has been found only on cetaceans of several species — both large and small — but shows a decided preference for blue whales. I have seen dozens clinging to the sides of a blue whale. Like many

of the blue whale's coterie of hangers-on, the whalesuckers are simply going along for the ride and catch their own food en route — a biological relationship called *phoresy*. One fish, however, is not such a harmless hitch-hiker. This is the Pacific lamprey (*Entosphenus tridentatus*) which uses its sucker-like mouth and sharp teeth to bite into the whale's skin, where it leaves characteristic scars.

Blue whales were too swift and powerful for the 19th Century whalers to pursue with their open boats and hand harpoons. In 1864, the Norwegian whaler, Sven Foy, invented the harpoon gun, and by the early 1900's blue whales, because of their large size, were the most sought-after target of whalers the world over. Floating factory ships and fleets of catcher boats pursued them far into the Antarctic pack ice. The slaughter reached a peak in the year 1931, when 29,649 blue whales were killed throughout the world. There was a brief respite during World War II, but after the war the slaughter continued. By 1966, the species was so scarce that it formed an insignificant portion of the world's whale catch, and the International Whaling Commission belatedly afforded the blue whale complete protection the world over. The original blue whale population in the 1900's probably numbered over 200,000. Today there are 15,000 in the Southern Hemisphere, 1500 in the North Pacific and a few hundred in the North Atlantic. □

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Hitch-hiking whalesuckers and lampreys ride a blue whale's back as it breaches for a breath in the Pacific. Photo by Dale W. Rice



AMERICAN PARTICIPATION IN TUNA FISHERY OF EASTERN TROPICAL ATLANTIC

Gary T. Sakagawa and William H. Lenarz

In the 1950s and early 1960s, Canadian and United States tuna vessels fished in the eastern tropical Atlantic on an exploratory basis. It was not until 1967 that a significant number of American (Canada, Panama, and U.S.) vessels entered the fishery. The fleet started with three boats in 1967 and increased to 24 boats in 1971 (Table 1). All but one have been purse seiners with capacity greater than 400 metric tons. Their catches have been almost exclusively yellowfin (*Thunnus albacares*) and skipjack (*Katsuwonus pelamis*) tunas. This report reviews the development of the yellowfin and skipjack tuna fisheries of the eastern tropical Atlantic with respect to the operations of the American fleet.

THE FISHERY

The area off west Africa between 25° N and 25° S latitude and east of 25° W longitude (Figure 1) is defined as the eastern tropical Atlantic. Many of the Atlantic tropical tunas, especially yellowfin and skipjack tunas, are caught there. The fishery was a local, subsistence industry until 1955. Then, French baitboats that traditionally had fished for albacore off southern Europe ventured south to fish for tropical tunas in the Dakar, Senegal region. The following year the Japanese longline fleet entered the fishery. Today, the fishery consists of baitboats and purse seiners of Canada, France, Ivory Coast,

Table 1. Catch (metric tons) and catch rate (catch/day's fishing)^{1/} of yellowfin and skipjack tunas caught by American seiners in the eastern tropical Atlantic

Year	Number of seiners	Yellowfin		Skipjack		Total	
		Catch	Catch rate	Catch	Catch rate	Catch	Catch rate
1967	3	978	7.6	473	3.7	1,451	11.3
1968	8	6,198	23.3	3,193	12.0	9,391	35.3
1969	25	19,845	10.9	4,440	2.4	24,285	13.3
1970	23	9,065	4.0	11,423	5.1	20,488	9.1
1971	24	3,750	2.5	16,875	10.3	20,625	12.8

^{1/} Catch rates for the American fleet are for large purse seiners. The rates are not directly comparable to those in Table 4 for the FIS seiners, because the catch rates of the FIS seiners are based on total effort of large and small seiners, which have different fishing powers.

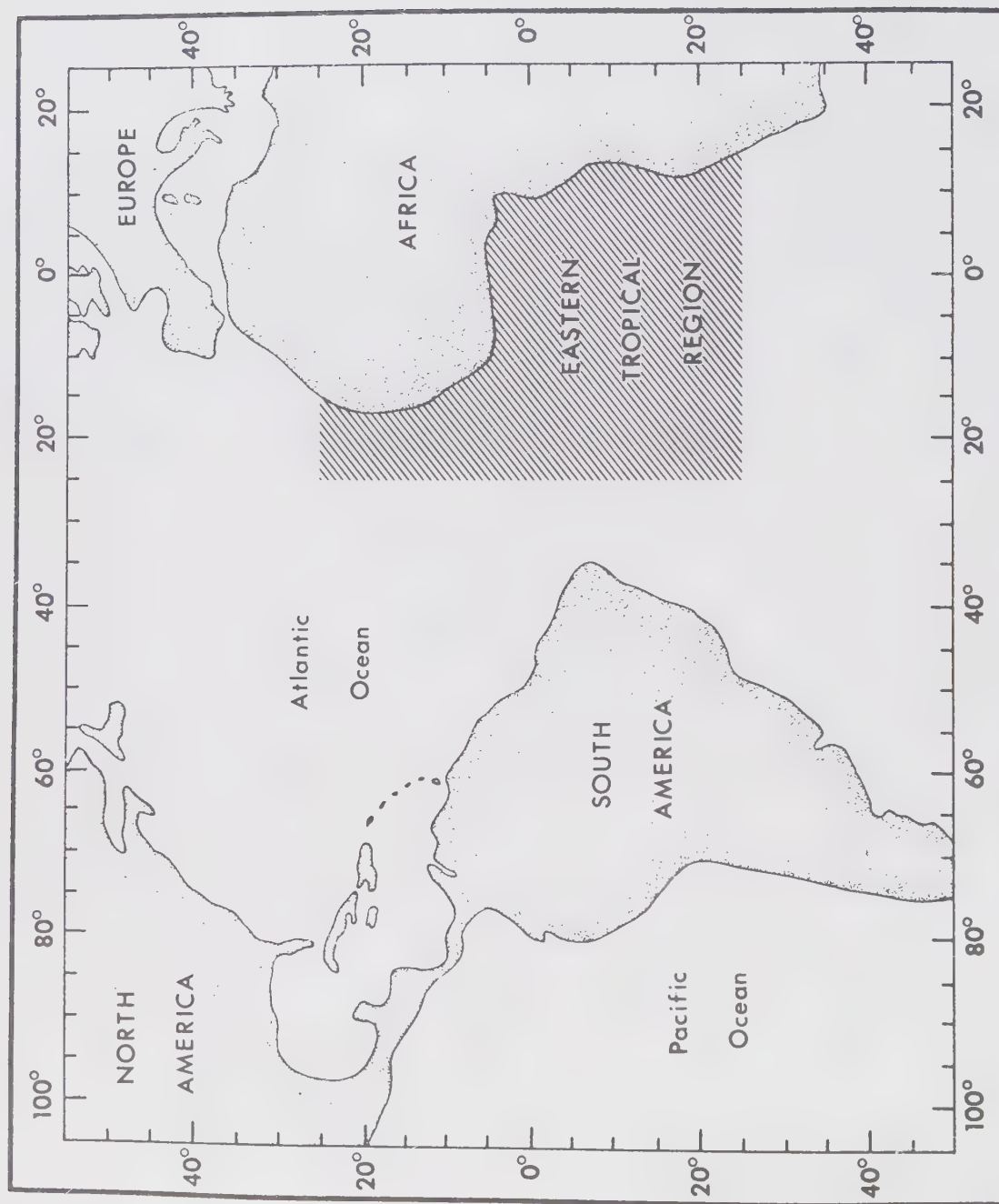


Fig. 1 - Map of the Atlantic Ocean showing the eastern tropical region.

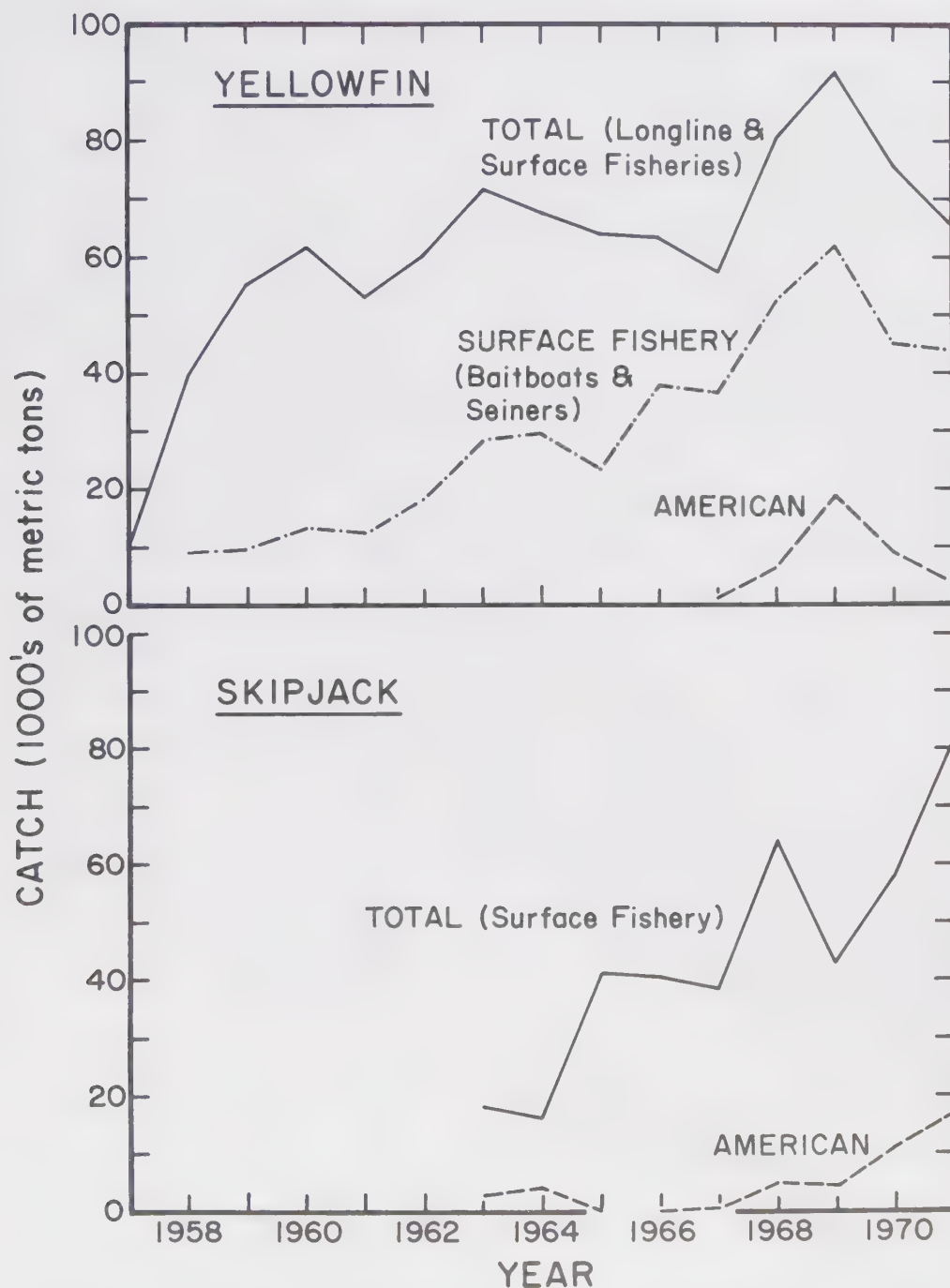


Fig. 2 - Catch of yellowfin and skipjack tunas from the Atlantic Ocean. Source of data is from Anonymous (1972).

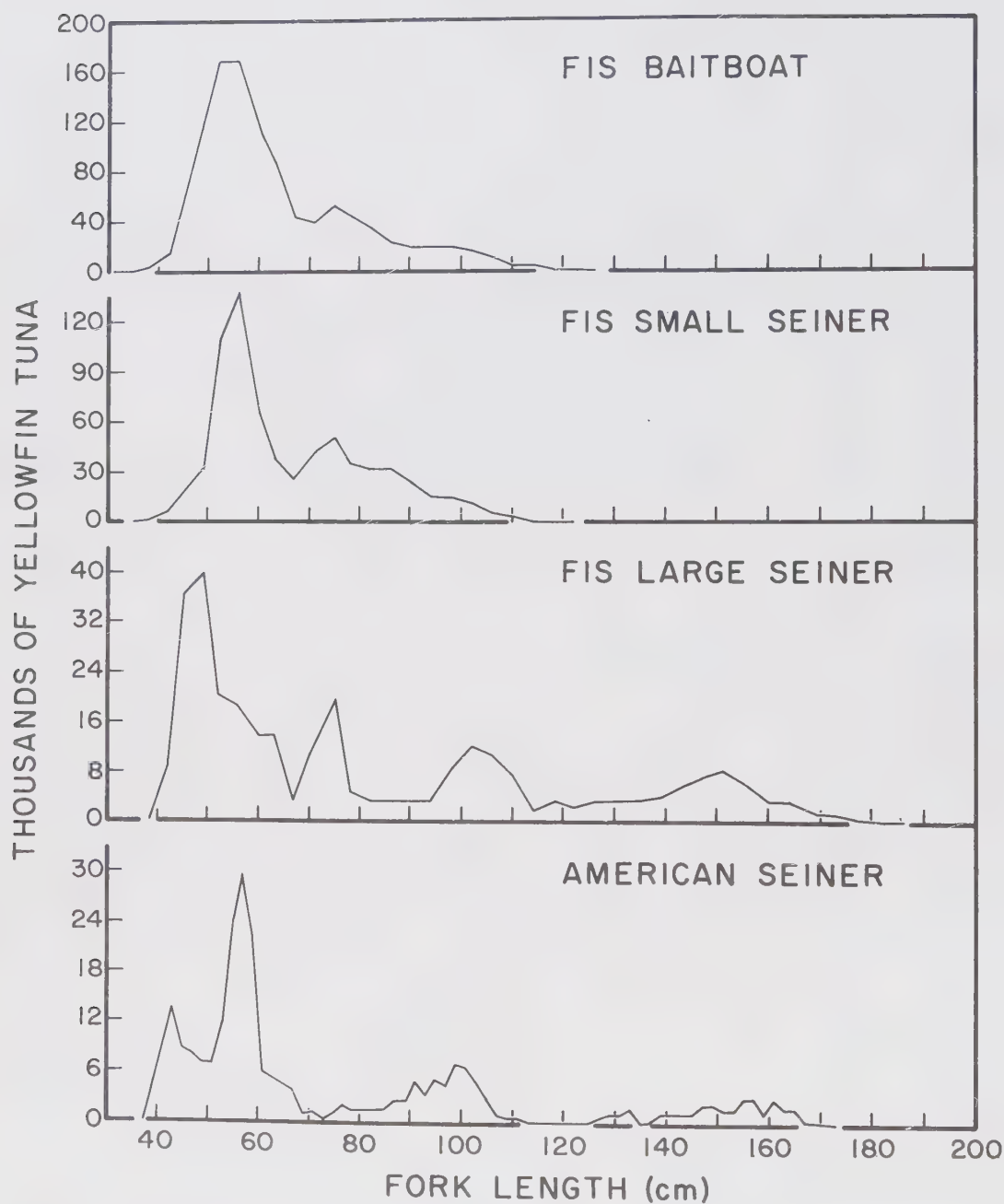


Fig. 3 - Length-frequency distribution of the 1971 catch of yellowfin tuna for French-Ivory Coast-Senegalese (FIS) and American vessels. Data for FIS vessels are from Anonymous (1972).

Japan, Norway, Panama, Portugal, Senegal, Spain, and the U.S.--and longliners of Korea, Japan, and Taiwan.

THE CATCHES

Yellowfin Tuna

In 1971, the total catch of yellowfin tuna from the Atlantic was 67,600 metric tons (Figure 2). This was lower than the high of 92,400 metric tons caught in 1969, and slightly lower than the 1961-70 average of 68,500 metric tons.

Since 1967, the American catch of Atlantic yellowfin tuna has been almost entirely from the eastern tropical Atlantic. The catch was 1,000 metric tons in 1967. It reached a high of 19,800 metric tons in 1969, dropped to 9,100 metric tons in 1970, and declined further to 3,800 metric tons in 1971 (Table 1). The decline in 1970 was due in part to a shift of fishing effort to skipjack tuna. The 1971 catch decline probably was due to a combination of decreased yellowfin fishing effort and increased availability of skipjack tuna.

The sizes of yellowfin tuna caught in 1971 by the American seners and French-Ivory

Table 2. Proportion of yellowfin and skipjack tunas in the combined catch (metric tons) of both species from the eastern tropical Atlantic

Nation and type of vessel	Year	Yellowfin Catch		Skipjack Catch		Total	
		Catch	%	Catch	%	Catch	%
French baitboat and purse seiner	1969	26,370	77.0	7,855	23.0	34,225	100
	1970	21,400	65.1	11,449	34.9	32,849	100
	1971	20,091	56.1	15,722	43.9	35,813	100
Ivory Coast baitboat and purse seiner	1970	590	58.9	412	41.1	1,002	100
	1971	1,126	57.0	848	43.0	1,974	100
Japanese baitboat and two-boat purse seiner	1963	900	8.9	9,200	91.1	10,100	100
	1964	2,600	45.6	3,100	54.4	5,700	100
	1965	2,400	22.9	8,100	77.1	10,500	100
	1966	5,300	47.7	5,800	52.3	11,100	100
	1967	6,500	52.4	5,900	47.6	12,400	100
	1968	7,900	36.7	13,600	63.3	21,500	100
	1969	6,800	53.5	5,900	46.5	12,700	100
	1970	2,400	24.2	7,500	75.8	9,900	100
	1971	5,300	26.5	14,700	73.5	20,000	100
Senegalese baitboat and purse seiner	1969	2,519	79.6	645	20.4	3,164	100
	1970	4,000	65.7	2,091	34.3	6,091	100
	1971	4,676	61.9	2,880	38.1	7,556	100
American purse seiner	1967	978	67.4	473	32.6	1,451	100
	1968	6,198	66.0	3,193	34.0	9,391	100
	1969	19,845	81.7	4,440	18.3	24,285	100
	1970	9,065	44.2	11,423	55.8	20,488	100
	1971	3,750	18.2	16,875	81.8	20,625	100

Table 3. Catch (metric tons) and catch rate (catch/day's fishing, in parentheses) of yellowfin and skipjack tunas caught by American seiners in the eastern tropical Atlantic

Year	May	June	July	Aug	Sept.	Oct.	Nov.	Dec.	Total
Yellowfin tuna									
1967					0(0)	477.2(7.7)	500.3(7.9)		977.5(7.6)
1968				2122.2(29.1)	2910.0(20.3)	1165.7(23.8)	0(0)		6197.3(23.3)
1969			607.8(6.3)	6814.8(16.7)	5219.1(9.9)	4011.1(7.5)	3192.3(13.3)	0(0)	19845.2(10.9)
1970	3.6(0.7)	633.2(4.1)	1458.4(3.3)	2963.1(5.0)	2091.0(4.0)	1451.2(3.5)	464.5(3.5)		9064.9(4.0)
1971		0(0)	398.6(6.5)	1620.8(7.7)	1350.0(2.4)	298.9(0.6)	81.7(0.5)		3750.0(2.5)
Skipjack tuna									
1967					0(0)	351.5(5.7)	121.1(1.9)		472.6(3.7)
1968				1211.8(16.6)	1319.8(9.2)	646.4(13.2)	15.4(15.4)		3193.3(12.0)
1969			146.1(1.5)	2217.2(5.4)	918.7(1.7)	1113.0(2.1)	45.4(0.2)	0(0)	4440.3(2.4)
1970	28.1(5.6)	986.2(6.4)	1332.6(3.0)	4303.6(7.3)	2289.4(4.4)	1846.3(4.4)	637.3(4.7)		11423.4(5.1)
1971		0(0)	423.6(6.3)	1101.9(4.8)	6964.3(11.5)	6944.1(12.9)	1441.1(7.5)		16875.0(10.3)

Table 4. Catch (metric tons) and catch rate (catch/day's fishing) $\frac{1}{2}$ by month of yellowfin and skipjack tunas caught by purse seiners of France, Ivory Coast and Senegal in the eastern tropical Atlantic
(Source of data is from Anonymous, 1972)

Month	1969						1970						1971			
	Yellowfin			Skipjack			Yellowfin			Skipjack			Yellowfin		Skipjack	
	Catch	rate	Catch	Catch	rate		Catch	rate	Catch	Catch	rate		Catch	rate	Catch	rate
January	926	3.63	516	2.02			2,835	6.70	171	0.40			1,204	2.03	825	1.39
February	535	3.99	157	1.17			529	1.90	91	0.33			963	1.85	579	1.11
March	523	6.32	244	2.95			1,302	3.02	29	0.07			787	1.79	688	1.57
April	657	6.69	41	0.42			1,051	1.76	375	0.63			751	1.35	1,138	2.05
May	669	5.04	186	1.40			678	2.49	670	2.46			637	1.09	1,077	1.84
June	3,254	10.75	179	0.59			2,247	5.38	1,841	4.41			2,053	4.19	1,675	3.41
July	1,692	6.61	499	1.95			1,091	2.36	396	0.86			1,409	2.70	1,672	3.20
August	1,842	4.17	389	0.88			2,202	3.34	1,162	1.76			3,331	4.97	4,144	6.19
September	1,391	2.72	139	0.27			2,643	4.77	1,328	2.40			2,243	4.85	928	2.01
October	842	2.44	442	1.28			1,735	2.88	1,845	3.06			1,413	2.30	1,182	1.92
November	1,073	2.56	614	1.47			1,190	1.99	1,130	1.89			1,033	1.59	7,355	11.33
December	988	2.04	272	0.56			391	0.99	268	0.68			1,888	2.71	1,796	2.58
Total	14,392	4.16	3,678	1.06			17,894	3.14	9,306	1.64			17,712	2.61	23,059	3.39

$\frac{1}{2}$ Catch rate is based on catch and effort of both large and small seiners. See footnote in Table 1.

Table 5. Catch (metric tons) and catch rate (catch/day's fishing), by month of yellowfin and skipjack tunas caught by baitboats of France, Ivory Coast and Senegal in the eastern tropical Atlantic (Source of data is from Anonymous, 1972)

Month	1969				1970				1971			
	Yellowfin		Skipjack		Yellowfin		Skipjack		Yellowfin		Skipjack	
	Catch	Catch rate	Catch	Catch rate	Catch	Catch rate	Catch	Catch rate	Catch	Catch rate	Catch	Catch rate
January	2,819	2.63	449	0.42	740	0.84	260	0.30	474	0.89	600	1.12
February	1,696	1.78	128	0.13	619	1.15	209	0.39	251	0.72	241	0.69
March	1,390	1.46	225	0.24	511	0.64	93	0.12	328	0.60	83	0.15
April	1,337	1.64	47	0.06	616	0.99	418	0.67	232	0.61	266	0.70
May	910	1.36	543	0.81	510	0.95	365	0.68	455	1.01	382	0.85
June	986	1.33	319	0.43	637	1.09	327	0.56	1,118	1.96	288	0.51
July	1,121	1.23	401	0.44	1,039	1.81	270	0.47	1,106	2.18	393	0.77
August	627	1.00	226	0.36	735	1.35	350	0.65	839	1.40	777	1.30
September	908	1.11	742	0.91	678	1.16	594	1.01	1,200	2.64	1,024	2.26
October	802	1.08	709	0.96	650	1.37	777	1.64	567	1.38	742	1.81
November	661	0.94	565	0.81	614	1.23	564	1.13	661	1.33	602	1.21
December	840	0.86	246	0.25	537	0.99	515	0.95	586	1.22	583	1.21
Total	14,097	1.41	4,600	0.46	7,884	1.10	4,742	0.66	7,817	1.35	5,981	1.03

Coast-Senegalese (FIS) baitboats and seiners are shown in Figure 3 (Anonymous, 1972). Fish caught by the American seiners are comparable in size to fish caught by FIS large seiners (>400 metric tons capacity). They are different from sizes of fish caught by FIS baitboats and small seiners (<400 metric tons capacity). The large seiners caught larger fish than the small seiners and baitboats. The reason is that large seiners use a larger and deeper net that catches the large, deep-swimming individuals of a school that fishing gears of small seiners or baitboats cannot catch.

Skipjack Tuna

The skipjack tuna resource of the Atlantic Ocean is considered to be large and under-

exploited (FAO, 1968). In the period 1965-71, the total annual catch averaged around 52,200 metric tons. The annual American catch prior to 1970 was under 5,000 metric tons. In 1970, the catch increased substantially to 11,400 metric tons, and to 16,900 metric tons in 1971. As with the American Atlantic catch of yellowfin tuna, most of the American Atlantic catch of skipjack tuna since 1966 has been from the eastern tropical region.

In American landings, the species mixture has changed from predominately yellowfin tuna in the 1960s to skipjack tuna in the 1970s (Table 2). This shift does not appear to be as pronounced in catches of other fleets that fished in eastern tropical Atlantic.

Table 6. Average catch rate (metric tons/day's fishing) of yellowfin and skipjack tuna for American purse seiners (1967-71) and French-Ivory Coast-Senegalese (FIS) purse seiners and baitboats (1969-71).
The maximum catch rates are underlined

Month	Yellowfin			Skipjack		
	American seiner	FIS		American seiner	FIS	
		seiner	baitboat		seiner	baitboat
January	-	3.91	1.63	-	1.19	0.53
February	-	2.17	1.40	-	0.89	0.31
March	-	2.74	0.97	-	1.01	0.17
April	-	1.07	1.20	-	1.24	0.40
May	0.72	2.01	1.13	5.62	1.95	0.78
June	3.96	<u>6.24</u>	1.45	6.16	3.05	0.49
July	4.13	3.38	<u>1.64</u>	3.19	2.07	0.53
August	<u>10.11</u>	4.16	1.24	6.93	3.22	0.76
September	6.64	4.11	1.50	6.59	1.57	1.27
October	4.76	2.56	1.24	<u>7.00</u>	2.22	<u>1.37</u>
November	6.94	1.08	1.14	3.70	<u>5.46</u>	1.02
December	0	2.07	0.98	0	1.48	0.67

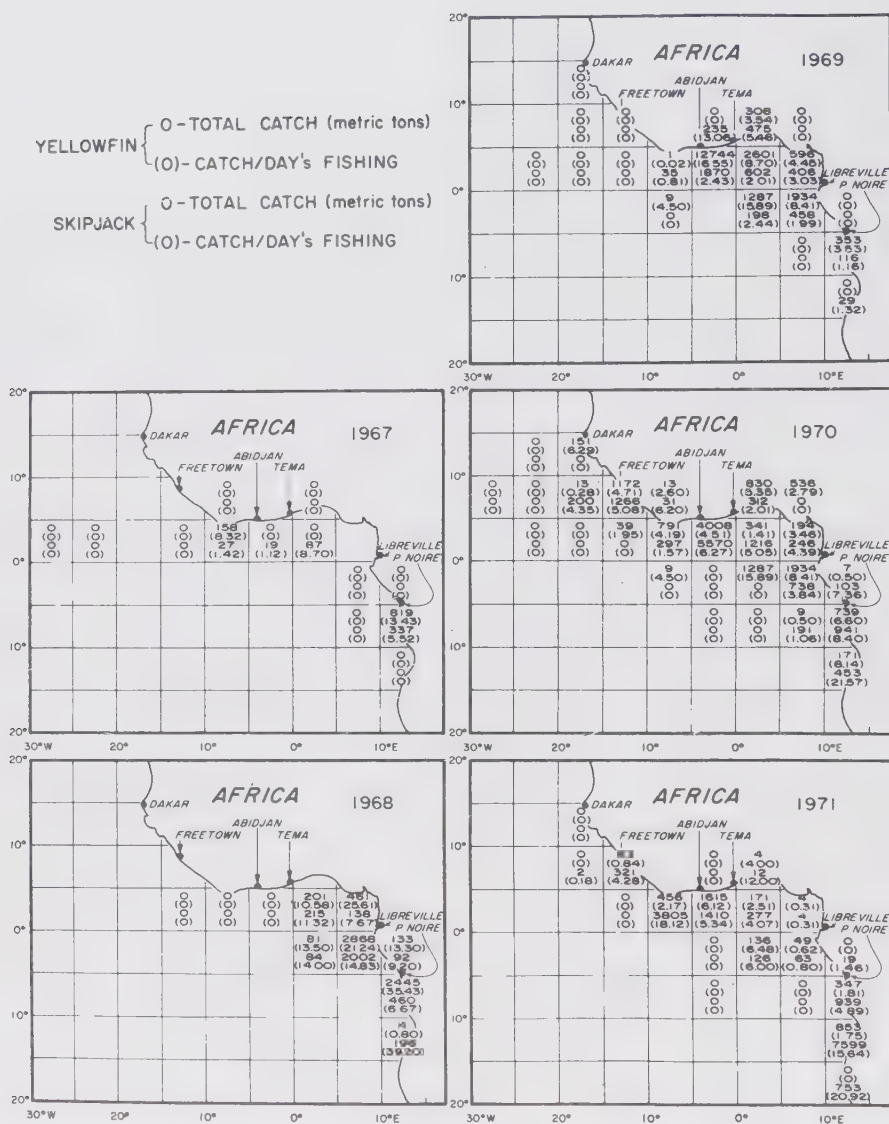


Fig. 4 - Total catch (metric tons) and catch rate (catch/day's fishing), in parentheses, of yellowfin and skipjack tunas caught by American seiners in 1967-71 by 5° x 5° areas.

LIMITED FISHING SEASON

Although tuna vessels of other nations, France and Spain, for example, fish in the eastern tropical Atlantic most of the year, the American fleet has fished there only during summer and fall (Table 3). The season for the American fleet is dictated largely by events in the eastern tropical Pacific. Most boats of the American fleet are based in California. They fish the eastern tropical Pacific from January until the yellowfin tuna catch quota is reached (Joseph, 1970). Since the catch rates in the eastern tropical Pacific are high, there has not been any incentive for the American boats to fish the more distant fishing grounds in the Atlantic before the close of the yellowfin season in the eastern Pacific.

The peak season (1967-71) for the American fleet has been August to November (Table 3). Peak season (1969-71) for the FIS fleet (baitboats and seiners) that fish year round has been summer and fall (Tables 4 and 5). Therefore, it appears that the American fleet is fishing during the period when yellowfin and skipjack tunas are most available in the areas presently being fished.

FISHING AREAS & CATCH RATES

The catch and catch rate for 1967-71 by $5^{\circ} \times 5^{\circ}$ areas for the American fleet are shown in Figure 4. The distribution of catches indicates that yellowfin and skipjack tunas are caught close inshore; most of the catch is made in the Gulf of Guinea. In 1971, a substantial amount of skipjack tuna also was caught off Angola. That was the first year in which the American fleet fished heavily (about 711 day's fishing) off Angola (south of 10° S); all its effort was concentrated in September and October. The results, therefore, cannot be judged at this time as typical for areas off Angola.

The catch rates for $5^{\circ} \times 5^{\circ}$ areas range from 0-34 metric tons/day's fishing for yellowfin tuna and 0-39 metric tons/day's fishing for skipjack tuna. The higher rates generally are associated with areas of low fishing effort. However, for some areas, such as off Angola in 1971 and off the Ivory Coast in 1969, the catch rate was high even when the fishing effort was high.

lowfin tuna and 0-39 metric tons/day's fishing for skipjack tuna. The higher rates generally are associated with areas of low fishing effort. However, for some areas, such as off Angola in 1971 and off the Ivory Coast in 1969, the catch rate was high even when the fishing effort was high.

Discussion

There is some evidence--decreasing catch per unit of effort with increase in effort, and smaller average sizes of fish in the catch--that suggests that the total catch of yellowfin tuna from the eastern tropical Atlantic would not increase appreciably if fishing effort is increased within the areas presently fished by each type of vessel (Anonymous, 1972). However, if the distribution of yellowfin tuna in the Atlantic is similar to that in the Pacific, the catch might presumably increase if the surface fishery (baitboats and seiners) is extended farther offshore into areas presently fished only by longliners.

From the point of fishing strategy of the American fleet, the question might be raised whether extending the fishing season would result in an appreciable increase in the fleet's catch and catch rate. Results for the FIS fleet suggest that this is possible (Tables 4 and 5). Most of the French catch of yellowfin and skipjack tunas are made during June to January, and the catch rates are relatively high (Table 6). On the other hand, the American catch and effort are concentrated in August to November. Thus, if the American fleet extends its fishing season into December and January, the fleet's total catch and catch rate probably would be increased.

Acknowledgments

We are indebted to the captains and owners of American tuna vessels who generously provided fishing statistics. The statistics were collected and processed by the Inter-American Tropical Tuna Commission.

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MONTHLY SEA LEVEL DIFFERENCES BETWEEN THE HAWAIIAN ISLANDS AND THE CALIFORNIA COAST

J. F. T. SAUR¹

ABSTRACT

Time series of monthly sea level differences, adjusted for linear trends and the isostatic effect of atmospheric pressure, are computed for Honolulu-minus-San Francisco (1905-69) and Hilo-minus-Avila (1947-59 and 1961-67) as an index to broad scale changes in current around the eastern limb of the North Pacific anticyclonic current gyre.

The normal seasonal cycle of sea level differences imply a net southeastward surface current that is strongest from April through October and weakest from December through February and the range is about 20% of the average. Nonseasonal differences for Honolulu-minus-San Francisco and Hilo-minus-Avila show a highly significant correlation over the 240 months of coincident records. Inferences regarding nonseasonal large-scale long-term changes in geostrophic current are drawn from the 65-year Honolulu-minus-San Francisco smoothed monthly anomalies in which variability of less than 6 months was suppressed, as follows: 1) nonseasonal changes in current speed exceed $\pm 10\%$ of the normal current over one-third of the time and range up to 54% of the normal monthly current, 2) the periods 1922-38 and 1950-54 were eras of low variability as compared with greater variability in the rest of the record, and 3) periods of weakest circulation were in 1911, 1918, 1941, 1957-58, and 1967, and of strongest circulation in 1915, 1920-21, 1943-44, 1948-49, and 1959.

For more than a decade there has been a rapidly growing interest of fishery scientists and biological oceanographers in the role of the environment in fishery problems. One objective is to include environmental effects in models of population dynamics and in fishery forecasting procedures. However, to do this, environmental characteristics which are significant to fisheries must be determined and set forth in quantitative form. One empirical approach to these complex environmental problems is to compile historical oceanic and atmospheric data into time series to gain a knowledge of the mean seasonal cycles and variability, identify periods of highly anomalous environmental conditions for further study, and seek an understanding of cause-effect relations which bring about the observed changes. Such an understanding would be useful for efficient monitoring of the oceanic envi-

ronment and in predicting environmental conditions.

Oceanographic data with good time and space distribution for time-series studies of environmental changes of a few months to several years are woefully scarce. Only sea-surface temperature observations taken by ships as a part of the marine weather observations have long-term continuity in time as well as oceanwide distribution. As a result, these have been used extensively in air-sea interaction studies and to indicate oceanic changes.

To augment the sea temperature data, mean sea levels compiled from continuous tidal records at coastal and island stations provide another source of long time-series data on ocean variability. The statistical characteristics and interrelations of the sea levels, atmospheric pressure, and temperature of many coastal and island stations in the Pacific have been described in several papers by Roden (1960, 1963, 1966) using autocorrelation, spectral, and coherence techniques.

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The data have been less utilized in the study of specific oceanographic changes. Stewart, Zetler, and Taylor (1958) pointed out the rise in sea level along the west coast of North America during the warming period of 1957-58. Bjerknes (1966) also noted changes in sea levels along the equator during El Niño, i.e., warming which occurs off the Pacific coast of South America, during the same 1957-58 period.

In this paper the use of sea level information in the northeast Pacific Ocean to augment inferences about oceanographic changes is explored. The geostrophic equation requires that the speed of the surface current be proportional to the transverse slope of the sea surface. Thus time series of differences in sea level between the Hawaiian Islands and the California coast could be an index to broad-scale changes in surface current in the eastern North Pacific Ocean. Some earlier exploratory work on sea level differences between Honolulu and San Francisco through 1962 was reported orally at meetings of the American Geophysical Union (Saur, 1966). These preliminary results indicated that a pronounced weakening of the strength of the south flowing current around the eastern limb of the North Pacific current gyre was associated with

the warm winters of 1940-41 and 1957-58, which have been reported for the California Current region (Reid, 1960; Robinson, 1961). The occurrence of El Niño in these same periods (Bjerknes, 1961, 1966) further indicated the possibility of a relaxation in strength of ocean current systems in the eastern Pacific on a broad scale.

No time series of direct observations of ocean conditions exist to study such broad-scale changes in current, and certainly not of the continuous nature of sea level data. In this paper therefore, the normal seasonal cycles of sea level differences between the Hawaiian Islands and the California coast are presented and some inferences are drawn from the 65-year record of Honolulu-minus-San Francisco differences about the character of changes of surface current in the region.

EARLIER STUDIES

Montgomery (1938) was the first to use the cross-current difference in sea level in the geostrophic equation to estimate the range of fluctuation of ocean current. Using changes in sea level difference between Charleston, S.C., and Bermuda, he found the range of seasonal variation was about 32% of the average difference. Stommel (1953) used fluctuations in cross-current sea level differences between Havana and Key West and between Cat Key and Miami as a measure of current in developing a model of the structure of the Florida Current. More recently, Wunsch, Hansen, and Zetler (1969) measured statistical variability of the Florida Current by spectral and coherence analyses of longer sea level records at the same four stations. They found that the apparent seasonal variation of the Florida Current accounts for only about 10% of the root-mean-square modulations for periods from 2 days to 1 year. They further concluded that monthly mean sea levels could be used to indicate long-period fluctuations.

Changes in mean sea levels at shore stations have been favorably compared by other investigators with changes in geopotential height of the sea surface in deep water offshore as traditionally determined from observed subsurface distribution of density of the water column. Mont-

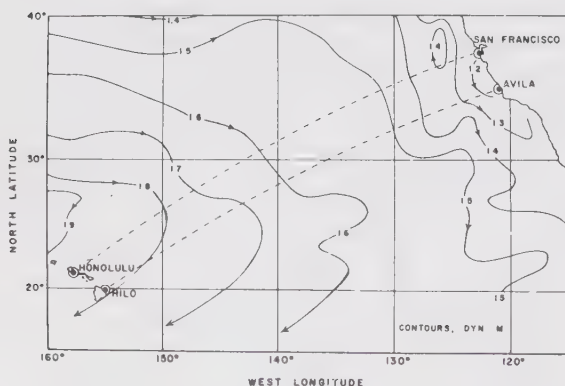


FIGURE 1.—Station locations and general pattern of surface currents (solid contours: geopotential anomaly at the sea surface relative to the 1,000 db surface, in dynamic meters) after the NORPAC Atlas (Oceanic Observations of the Pacific, 1960) but modified near the Hawaiian Islands per Reid (1961) and Seckel (1962). Dashed lines are great circles joining pairs of tide stations for which sea level differences are calculated.

gomery (1938) cautioned that he had only a meager number of hydrographic stations for this, but other studies since that time tended to confirm his results.

For the southern California coast, LaFond (1939) found good agreement between weekly sea level and contours of dynamic height (0/500 db) extrapolated to the tide station. Special observations of sea level and temperature structure were carried out at many island stations during the International Geophysical Year from which Lisitzin and Pattullo (1961) concluded that in the open ocean most of the deviations from mean sea level can be explained by combined atmospheric pressure effects and steric effects, the latter being defined as those due to changes in the specific volume of the water column, i.e., those measured by dynamic height anomalies. Shaw and Donn (1964) had 173 hydrographic stations, taken approximately bi-weekly by the *Panulirus* off Bermuda over a period of nearly $7\frac{1}{2}$ years, to compute steric levels for comparison with sea levels. They found that about 80% of the variance of raw sea levels, which included the seasonal cycle, resulted from a combination of the atmospheric pressure effect, which was weak, and the steric effect, which was dominant.

Sturges (1966) has shown high correlations between steric levels and mean sea level at two Pacific coast locations. The least squares regression of steric levels computed for the coast against 3-day sea level (adjusted for atmospheric pressure) for Neah Bay, Wash., was 0.97 with a standard error of estimate of 4.1 cm and a correlation of 0.904. The regression coefficient at San Diego, Calif., was only 0.61 with a standard error of estimate of 2.2 cm and a correlation of 0.914. Theoretically, for variations of sea level adjusted for pressure to agree with steric level, the slope of the regression should be unity. Sturges also estimated the wind set-up effect at Neah Bay, which has a narrow continental shelf, to be negligible.

Such studies indicate, as summarized by Donn, Pattullo, and Shaw (1964), that the combined atmospheric pressure and steric effects account for most of the sea level variations of periods longer than a few months. Thus, the interpre-

tations made here assume that sea level differences, suitably adjusted for trends and atmospheric pressure, are a reasonable measure of changes in broad-scale geostrophic currents.

SURFACE CURRENTS OF THE REGION

Our area of interest is shown in Figure 1. Sea level differences between Honolulu and San Francisco and between Hilo and Avila are to be studied. The great circles joining each pair of stations span the same region of the eastern North Pacific Ocean.

The currents in the region are part of the eastern limb of the major anticyclonic current gyre of the North Pacific Ocean. The general pattern is shown in Figure 1 by the 0/1,000 db contours of dynamic height anomaly. The surface current is generally to the southeast, nearly normal to the great circles over most of the distance. At these latitudes the California Current extends from the California coast to about long 130°W , or somewhat farther, and about one-half of the change in geopotential anomaly takes place across this current, i.e., in less than one-third the distance between the stations. As a typical eastern boundary current (Wooster and Reid, 1963), it is broad, sluggish, and reinforced by coastal upwelling during the spring and summer months. During the winter months, December through February, a narrow north flowing countercurrent, often referred to as the Davidson Current, frequently occurs at the surface along the central California coast.

The California Current feeds into the North Equatorial Current, the axis of which lies south of lat 20°N (Seckel, 1962) so that there is generally a southward component across the great circle near the Hawaiian Islands. Occasionally, however, there is a west-northwestward flow along the east side of the islands, as evidently occurred at the time of the 1955 Norpac survey (Oceanic Observations of the Pacific, 1960). Corresponding to this return flow across the great circle, the sea levels at the Hawaiian stations would be lower than sea level northeast of the islands. Such localized conditions cannot be revealed by the sea level data, and thus are one source of "noise" in the data.

DATA AND PROCEDURES

Monthly mean sea levels were obtained from the National Ocean Survey² which has for many years compiled these data for its tide stations. The coincident period of record for Honolulu and San Francisco is 65 years, 1905-69. The coincident period for Hilo and Avila is 20 years, 1947-59 and 1961-67. It is broken and shortened because of incomplete records at Avila. However, Avila was selected among other California stations to pair with Hilo, so that the great circle between them would be close to that joining Honolulu and San Francisco and would cross essentially the same currents.

All of the tide gauges have moderately good exposure. Hilo and Avila are small coastal harbors protected by artificial breakwaters. The Honolulu gauge is in the outer of two harbor areas just inside of the entrance channel. The San Francisco gauge is at Fort Point just below the Golden Gate Bridge on the south side of the entrance to San Francisco Bay. Depths of 100 fm (183 m) are less than 10 km offshore from Hilo and Honolulu tide gauges, less than 20 km off Avila, and about 55 km off San Francisco.

ELIMINATION OF TRENDS

The sea level observations refer to the level of the ocean surface relative to the adjacent land. The annual mean sea levels at each of the four stations increase irregularly with time as shown in Figure 2. Such long-term trends as are due to a combination of change in the total mass of ocean water by melting (or accretion) of glaciers and of local subsidence (or emergence) of the land on which the gauge is located (Hicks and Shofnos, 1965), need to be eliminated from the data.

The linear trends determined by least squares regression, of 0.17 cm/year at Honolulu and 0.20 cm/year at San Francisco (Figure 2) are essentially the same as reported by Hicks and Shofnos (1965) for sea levels through 1962 at

the same stations. The trend of 0.24 cm/year at Avila is only slightly larger than the first two, but the trend of 0.57 cm/year at Hilo is well over twice as large. In a computer analysis of the tide records at five stations in the Hawaiian Islands, Moore (1971) found a pattern of near zero trend at the older islands to the northwest increasing consistently toward the southeastern younger islands. Moore attributes the greater trend at Hilo to subsidence caused by loading of the crust by active volcanism. An interesting study by Apple and MacDonald (1966) of archeological features—native bait cups, net tanning tubs, and playing boards—carved into a newly submerged reef at Honaunau, Hawaii, further indicates a century of subsidence like that indicated by the recent tide gauge records.

By an indirect method using the decay constant of the autocorrelation coefficient Roden (1966) examined the consistency of trends for moving 30-year periods in the longer records at Honolulu and San Francisco. He found that the 30-year trends at Honolulu varied irregularly from 0.12 cm/year to 0.25 cm/year. At San Francisco the trends were low (about 0.05 cm/year) for the 1904-35 period, rising gradually and leveling off at about 0.25 cm/year for 30-year periods starting after 1915. Since not enough is known about the possible meteorological and oceanographic contributions to these trends, only the long-term linear trends shown in Figure 2 have been eliminated.

ADJUSTMENT FOR ATMOSPHERIC PRESSURE

There is general agreement that for periods of 1 month or more the ocean maintains an isostatic equilibrium with changes in atmospheric pressure. Assuming the average pressure over the whole ocean to be constant, if the pressure difference between two locations changes, the elevation of the sea surface changes in a compensatory manner so that there is no change in distribution of pressure on the sea floor. There is no balancing current associated with this portion of the slope of the sea surface which is balanced by the atmospheric pressure gradient. There-

² Formerly the Coast and Geodetic Survey, Environmental Science Services Administration.

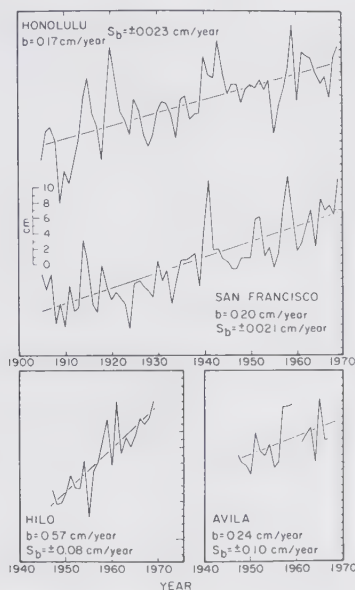


FIGURE 2.—Changes in annual mean sea level at four tide stations and linear trends determined by least squares regression. Slope of regression, b , and standard error of regression, s_b , are shown.

fore, an adjustment for this “inverted barometer” effect is made by correcting the sea levels to a “normal” atmospheric pressure which compensates for both the normal seasonal cycle and the monthly anomaly of atmospheric pressure at the station. For our purpose a correction of 1 cm in sea level for 1 mb change in atmospheric pressure is sufficiently accurate. Adjustments of less than 1 cm for monthly deviations of mean atmospheric pressure over the world oceans reported by Pattullo et al. (1955) have not been made to the individual station data reported here, because they are small and would have no effect on sea level differences.

Monthly mean atmospheric pressure reduced to sea level from weather observations of the National Weather Service at Honolulu, San Francisco, Hilo, and Santa Maria (less than 20 nautical miles from Avila) were obtained mainly from published sources. The World Weather Record series (Clayton, 1944a, 1944b; Clayton and Clayton, 1947; U.S. Weather Bureau, 1959, 1965, 1968) contain climatological data, includ-

ing monthly atmospheric pressure, through 1960. Monthly mean pressures for first order weather stations are included in the monthly issues of Climatological Data, National Summary, U.S. Environmental Data Service, published since January 1950. Some manuscript records obtained directly from the Weather Service offices were helpful in standardizing all pressure data to sea level.

NORMAL SEASONAL CYCLES OF SEA LEVEL AND SEA LEVEL DIFFERENCE

The *normal* monthly sea levels are obtained by averaging the monthly sea levels³ for a given month from all years of record. Because the zero level for the scale on the tide gauge is arbitrary at each station the normal monthly sea levels are shown in Table 1 in terms of departure from the long-term mean for all months and years. The standard deviations for given months in Table 1 are measures of the year-to-year variability of monthly sea level for the given month. From these one can compute that the 95% confidence limits on the monthly normals for Honolulu and San Francisco are 0.8 cm or less, and 1.4 cm or less for Hilo and Avila.

We are interested in the real differences in normal monthly sea level between stations as a base against which to measure the variability. For continental stations it is possible to determine this difference of long-term mean sea level between two stations by reference to the geodetic leveling network,⁴ but no such reference leveling exists between the continent and Hawaiian Islands. As described in the next section, the long-term sea level difference has been estimated using oceanographic data.

COMPUTATION OF LONG-TERM MEAN SEA LEVEL DIFFERENCE

The long-term mean sea level differences between Honolulu and San Francisco and between

³ Monthly sea level with trend removed and adjusted to normal atmospheric pressure is hereafter implied.

⁴ From oceanographic data, however, Sturges (1966) suggests there may be some systematic north-south leveling error.

TABLE 1.—Departures of normal monthly sea level, $\bar{h}$, from the long-term mean at each tide station; normal monthly sea level difference, $\bar{d}$; and standard deviations, s , of monthly values for total years of record, in centimeters. Honolulu and San Francisco, 1905-69; Hilo and Avila, 1947-59 and 1961-67.

Month	Honolulu		San Francisco		Honolulu-San Francisco		Hilo		Avila		Hilo-Avila	
	$\bar{h}$	s_h	$\bar{h}$	s_h	$\bar{d}$	s_d	$\bar{h}$	s_h	$\bar{h}$	s_h	$\bar{d}$	s_d
Jan.	-1.9	4.4	5.4	5.3	50.6	6.9	-2.0	4.2	4.6	4.4	46.0	4.2
Feb.	-1.7	4.4	4.4	6.3	51.9	6.8	-3.1	3.7	1.1	4.3	47.6	4.4
Mar.	-1.7	5.1	-1.1	6.0	57.4	7.6	-2.9	5.1	-4.6	3.8	53.3	6.3
Apr.	-2.8	5.3	-5.1	4.6	60.3	7.2	-2.2	4.2	-6.9	3.5	56.6	6.0
May	-2.6	5.1	-6.3	3.4	61.7	5.8	-3.3	5.3	-6.6	3.6	55.7	5.6
June	-2.0	5.6	-4.6	2.6	60.6	6.3	-2.5	5.9	-4.3	2.9	53.9	6.0
July	0.3	5.8	-1.3	2.8	59.6	6.4	0.9	5.0	0.0	3.6	53.3	5.2
Aug.	2.6	5.5	-0.5	2.8	61.1	5.8	4.0	4.6	2.2	3.6	53.9	4.7
Sept.	3.7	4.7	1.0	3.2	60.8	5.7	4.4	4.7	3.2	3.7	53.1	6.4
Oct.	3.7	4.7	1.0	3.7	60.7	6.1	4.1	3.5	3.2	4.4	52.9	4.5
Nov.	2.1	3.9	2.3	4.4	57.8	5.8	2.8	4.3	3.8	3.7	50.6	4.8
Dec.	0.1	4.5	4.6	4.9	53.5	6.3	0.0	5.1	4.4	5.1	47.0	5.5

Note: Long-term mean differences, Honolulu-minus-San Francisco and Hilo-minus-Avila, have been adjusted to 58 cm and 52 cm, respectively, by reference to 0/1,000 db dynamic heights, as described in text.

Hilo and Avila have been estimated from 0/1,000 db dynamic height anomalies. Reed (1970) has shown that the real topography of the 1,000 db surface between Honolulu and San Francisco is probably 1 cm or less.

The dynamic height anomalies were obtained from listings of hydrographic station data supplied by the National Oceanographic Data Center and data reports of the Trade Wind Zone Oceanography (TWZO) Program (Charnell, Au, and Seckel, 1967a, b, c, d, e, f).

Information on the number of stations, location, and average dynamic height anomalies is given in Table 2. The locations of the hydrographic stations relative to the tide stations are shown in Figure 3. Frequent observations made since 1949 by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) made it possible to get a good sampling of stations very near the two California tide stations. The density of sampling was much lower near the Hawaiian Islands, so observations over broader geographic regions were used. The mean dynamic height anomalies were computed for several independent sets of observations in the vicinity of Honolulu and Hilo to reveal the extent of island effects, but no large differences were found in the averages.

All oceanographic stations were taken since 1947. Sampling of different months throughout the year was good. Long-term mean Honolulu-minus-San Francisco sea level difference was

found to be 58 cm and the Hilo-minus-Avila difference was 52 cm. The normal monthly sea level differences in Table 1 reflect the adjustment of long-term mean sea level differences to these values.

HONOLULU-MINUS-SAN FRANCISCO

The seasonal variation of the normal monthly sea level difference for Honolulu-minus-San Francisco sea level difference is shown in the upper part of Figure 4. The cycle is asymmetric about the mean level. The monthly difference is high, forming a plateau, in the months from April through October, and a sharp minimum occurs from December through February. March and November are transitional months. The range of the normal seasonal cycle is 11 cm or 19% of the long-term mean difference of 58 cm.

The lower part of Figure 4 shows how the normal seasonal cycles at each station contribute to the seasonal cycle of the difference. The monthly normal at San Francisco is lowest in May, early in the upwelling season. The Honolulu sea level is also at its minimum, but the magnitude of the negative departure at San Francisco is more than double that at Honolulu and the normal cycle of sea level difference is at its maximum. Both station curves rise at nearly the same rate from June to October. A somewhat more rapid rise in July at San Francisco,

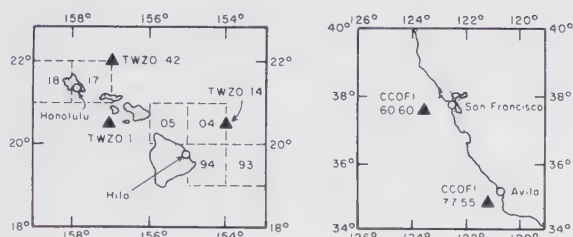


FIGURE 3.—Locations of hydrographic station data used to determine long-term differences in sea level as referred to in text and in Table 2. CCOFI = California Cooperative Oceanic Fisheries Investigations. TWZO = Trade Wind Zone Oceanography program. Two-digit numbers are 1-degree square (dashed lines) identification used in National Oceanographic Data Center listings of hydrographic station data.

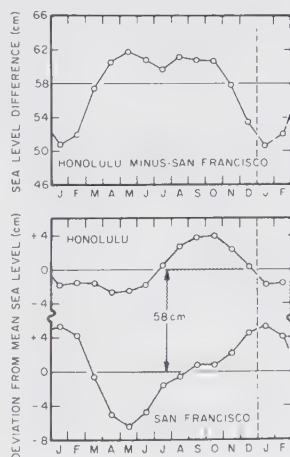


FIGURE 4.—Seasonal deviations of 65-year normal (1905-69) monthly sea levels (trend removed and adjusted to normal pressure) from long-term mean, Honolulu and San Francisco (below). Seasonal cycle of normal monthly sea level difference (above). Difference of long-term mean sea level of 58 cm was determined from hydrographic station data (see text).

probably due to heating, giving way to a more gradual rise into autumn, results in a slight dip during July in the plateau of the difference. The sea level at Honolulu drops rapidly from October to January. At San Francisco, however, the sea level continues to rise from November to its highest value in January. Some of this rise is undoubtedly the result of the frequent occurrence of the north-flowing coastal countercurrent

in these months (Reid, Roden, and Wyllie, 1958), while some may be due to decrease in the speed of the south-flowing current offshore. The proportions cannot be determined from the sea level data. The combined changes at Honolulu and at San Francisco result in a sharp winter minimum in the normal cycle of sea level difference.

HILO-MINUS-AVILA

The seasonal variation of the normal monthly sea level difference for Hilo-minus-Avila (Figure 5) is similar to that for Honolulu-San Francisco. A winter minimum occurs in December-February, and the maximum occurs in the spring. However, after a decrease of a few centimeters to July the normal difference remains at a nearly constant level through October rather than rising again as it did for Honolulu-San Francisco. March and November are transitional months except that March has a normal difference as high as those for late summer. The range of the normal seasonal cycle

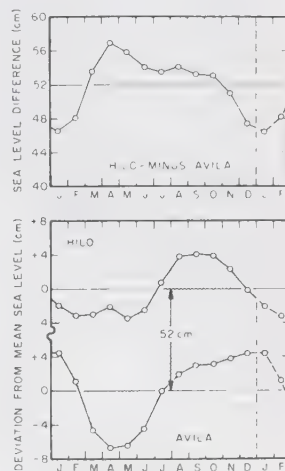


FIGURE 5.—Seasonal deviations of 20-year normal (1947-59, 1961-67) monthly sea level (trend removed and adjusted to normal pressure) from long-term mean, Hilo and Avila (below). Seasonal cycle of normal monthly sea level difference (above). Difference between long-term mean sea level of 52 cm was determined from hydrographic station data (see text).

is 10.6 cm, or 20% of the long-term mean sea level difference of 52 cm.

The seasonal cycle for Hilo is very much like that at Honolulu. The slight peak in April at Hilo, which does not occur at Honolulu, combined with the April minimum at Avila causes the maximum in the sea level difference to occur 1 month earlier for Hilo-Avila than for Honolulu-San Francisco. The normal seasonal cycle at Avila tends to lead that at San Francisco by 1 month. A stronger rise occurs at Avila in June-August than at San Francisco, which may be a heating effect because Avila is at a lower latitude.

DISCUSSION

The characteristics of the normal seasonal cycles of sea level difference for both pairs of stations are in agreement with each other and in accord with our knowledge from other sources of the oceanography of the northeast Pacific and California Current. The geostrophic equation requires that the speed of the surface current be proportional to the transverse slope of the sea surface. From the sea level difference we can infer that the average current normal to the great circles between the Hawaiian Islands and the California coast is southeastward throughout the year. It is strongest in the upwelling and summer season when the North Pacific atmospheric high pressure cell is best developed. It is weakest during the winter season.

Using an average latitude between stations and the long-term differences in the geostrophic equation, the average current to the southeast is 2.0 cm/sec for the Honolulu-San Francisco difference and 1.9 cm/sec for the Hilo-Avila difference. The range of the normal seasonal cycle, as noted earlier, is 20%.

It must be kept in mind that the sea level difference indicates only the average geostrophic surface current normal to the line between the two stations. For the California Current the contours of 0/500 db dynamic height anomaly in the CalCOFI Atlas No. 4, Geostrophic Flow (Wyllie, 1966) indicate that the speed averaged over a distance of 1,000 km is about 5 to 10 cm/

sec, whereas there may be narrow regions about 100 km in width with current of 25 cm/sec, or greater.

COMPARISON OF MONTHLY SEA LEVELS WITH STERIC LEVELS

Monthly sea level differences are to be used to estimate the slope of the sea surface and draw inferences regarding month-to-month and year-to-year changes in current from the geostrophic equation. Traditionally the slope is estimated indirectly by computing geopotential heights, or steric levels. Therefore, the agreement between monthly sea levels and steric levels at nearby offshore locations was investigated using hydrographic station data, employed earlier to establish the long-term mean differences in sea level between pairs of stations. Correlation coefficients between the monthly sea levels, linearly interpolated to the date of each hydrographic station, and the steric levels are given in the last column of Table 2. For San Francisco and Avila, where a large number of hydrographic stations were made within a small area at nearby locations, the correlation coefficients are 0.54 and 0.57 respectively. Both coefficients are considerably higher than the 1% level of significance.

For Honolulu the correlations from four sets of data from different areas are quite consistent, ranging from 0.54 to 0.65. These coefficients are as large as those for San Francisco and Avila, but because of the smaller sample sizes are statistically significant only at the 5% level.

For Hilo the correlations for three different sets of steric levels are less consistent. A high correlation, $r = 0.78$, which is significant at the 1% level, was obtained with Hilo monthly sea levels only from the set of 10 steric levels from observations in 1-degree squares 04 and 05 immediately northeast of Hilo. Dynamic topography charts in TWZO data reports (Charnell et al., 1967a, b, c, d, e, f) reveal that the presence of an anticyclonic eddy or ridge northeast of Hilo at TWZO station 14 during 5 of the 16 observational periods caused the lower correlation of data from that station with Hilo sea levels. One suspects some similar local effect as

TABLE 2.—Determinations of long-term mean sea level differences from 0/1,000 db geopotential (steric) anomalies at nearby offshore locations. Correlations, r , of monthly sea levels with geopotential anomalies.

Shore station	Data source	Location of hydrographic stations (see Figure 3)	Distance from shore station (km)	No. of observations	Average steric anomaly, 0/1,000 db (dyn cm)	Correlation, r steric vs. sea level
Honolulu	NODC	1-degree square 17, Marsden square 088	10-100	10	¹ 182.4	0.65*
	NODC	1-degree square 18, Marsden square 088	30-120	12	¹ 182.2	0.64*
	TWZO	Station 1	100	16	184.3	0.60*
	TWZO	Station 42	120	15	184.0	0.54*
San Francisco	NODC	CalCOFI 60.60	105	52	² 125.2	0.54**
Long-term mean sea level difference, Honolulu-minus-San Francisco = 58 cm						
Hilo	NODC	1-degree squares 04, 05, Marsden square 088	10-150	11	¹ 179.5	0.78**
	NODC	1-degree squares 93, 94; Marsden square 052	20-200	10	¹ 179.3	0.48
	TWZO	Station 14	140	16	181.1	0.42
Avila	NODC	CalCOFI 77.55	50	42	³ 127.5	0.57**
Long-term mean sea level difference, Hilo-minus-Avila = 52 cm						

¹ 0/500 db average plus 49.0 dyn cm for 500/1,000 db average, based on TWZO data and 1,000 m stations.² 0/500 db average plus 45.9 dyn cm for 500/1,000 db average, based on 37 stations in same 1-degree square.³ 0/400 db average plus 57.9 dyn cm for 400/1,000 db average, based on 25 stations in same 1-degree square.

* Correlation significant at 5% level.

** Correlation significant at 1% level.

the cause of the lower correlation for observations in 1-degree squares 93 and 95.

The correlations between monthly sea levels and offshore steric levels for the four stations in this study are less than anticipated from the results reported by other investigators, e.g., Shaw and Donn (1964) and Sturges (1966), as noted in the section, Earlier Studies. It is suspected that the lower correlations for the four Pacific stations in the present study may be due in part to comparison of a monthly sea level with a steric level from a single hydrographic observation on a given day. Present available steric data explain only about 40% of the variance of monthly sea levels from which the trend has been removed and which have been adjusted to normal pressure. As suggested by Stommel (1958) in relation to sea level at Bermuda, the possibility exists that geostrophically balanced barotropic currents exist which would also affect the monthly mean sea levels. When time series of frequent hydrographic observations or long-term observations from buoys become available to give a better estimate of continuous changes in steric level, we may then be able to attain a better understanding of the causes of sea level variations. For the present the unexplained variability may limit the use of sea levels and sea level

differences to interpretation of broad-scale, highly anomalous oceanic changes.

NONSEASONAL SEA LEVEL DIFFERENCES

The monthly sea level differences used in this study are given in Appendix Tables 1 and 2 for Honolulu-minus-San Francisco and Hilo-minus-Avila, respectively. For each station the linear trends were removed and values adjusted to normal atmospheric pressure. The monthly differences reflect the adjustment, previously discussed, of the long-term mean sea level difference for all months and years to a mean difference determined from 0/1,000 db geopotential heights.

VARIABILITY

The nonseasonal variations are represented by the monthly anomalies, defined as the difference between the value for the month and the normal for the same month. The standard deviations in Table 1 for given months at individual stations exhibit the same characteristics as those reported in an earlier study (Saur, 1962) for six Pacific

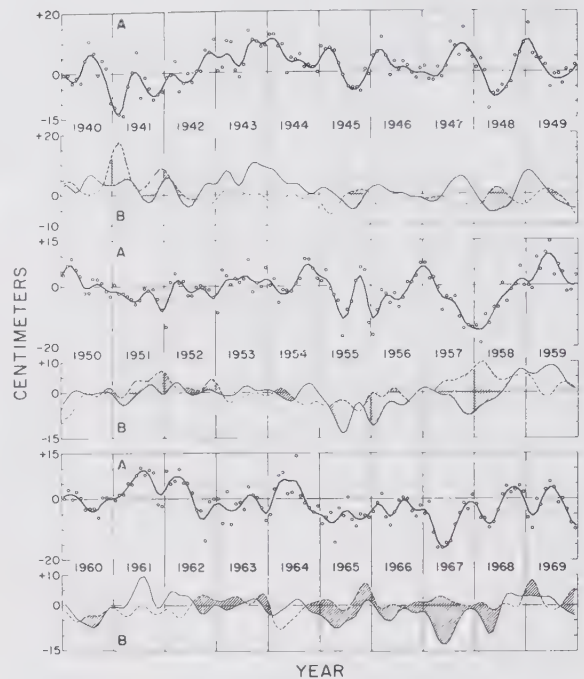
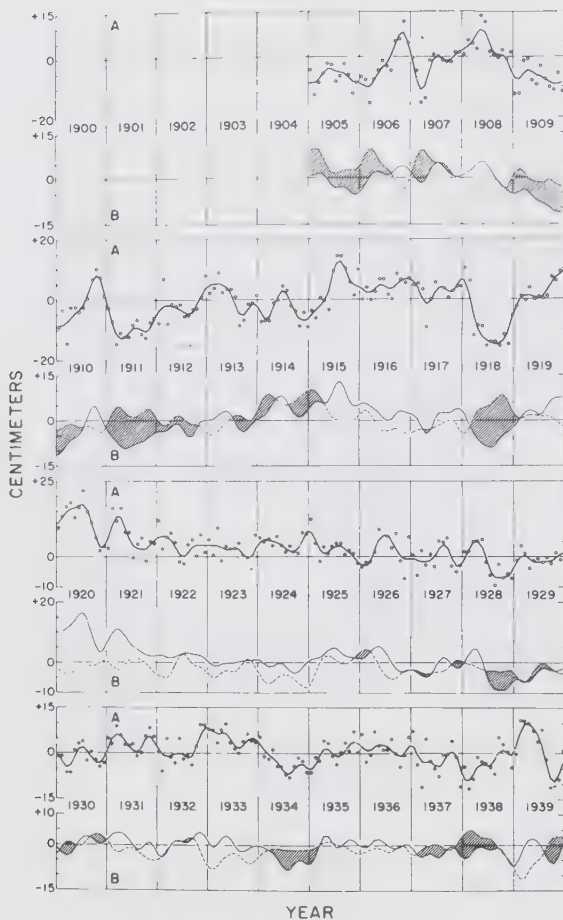


FIGURE 6.—Monthly sea levels (trend removed and adjusted to normal atmospheric pressure). Honolulu and San Francisco, 1905-69. A. Unsmoothed anomalies (circles) and smoothed anomalies (solid curve) for difference, Honolulu-minus-San Francisco. B. Smoothed anomalies for Honolulu (solid curve) and San Francisco (dashed curve). Shaded areas show periods when anomaly of difference is negative.

stations, two of which were Honolulu and San Francisco. Standard deviations in the former study were slightly larger because trends were not eliminated. At San Francisco, a coastal station at mid-latitude, the standard deviations show a seasonal change, attaining values near 6 cm in the late winter but decreasing to less than 3 cm in summer. At the other stations they vary less with season and those at the island stations generally lie in the range between 4.0 and 5.5 cm.

The standard deviations of the monthly sea level differences (Table 1) do not vary greatly throughout the year. The Honolulu-minus-San Francisco values are slightly larger than those for Hilo-minus-Avila because "climatic" changes,

to be discussed later, appear in the longer Honolulu-San Francisco records.

The time series of the anomalies of monthly sea level difference are shown by open circles in Figure 6 for Honolulu-minus-San Francisco and in Figure 7 for Hilo-minus-Avila. The variability indicated by the standard deviations is evident. To suppress the shorter period variability and aid in detecting underlying longer period changes the time series have been smoothed, as indicated by the solid curves.

A simple 5-point smoothing operator with weights of $-1/16$, $1/4$, $5/8$, $1/4$, $-1/16$ was selected for the smoothing. This is a particular case of one-dimensional, two-element smoothers described by Shapiro (1970). It is a low-pass filter with a response function:

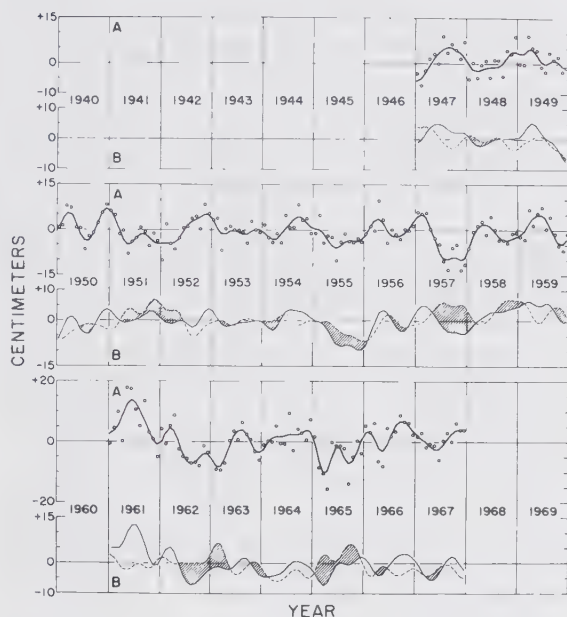


FIGURE 7.—Monthly sea levels (trend removed and adjusted to normal atmospheric pressure). Hilo and Avila, 1947-59 and 1961-67. A. Unsmoothed anomalies (circles) and smoothed anomalies (solid curve) for difference, Hilo-minus-Avila. B. Smoothed anomalies for Hilo (solid curve) and Avila (dashed curve). Shaded areas show periods when anomaly of difference is negative.

$$R(n) = 1 - \sin^4 \frac{\pi}{n}$$

where n is the number of data intervals in the Fourier component being smoothed. In our case n is also the wave period in months. Periods of 2 months are eliminated completely in one application of the smoother. Repeated applications of the smoother eliminate or reduce progressively longer periods. The response is a positive value between zero and one for all finite wave periods, so no 180° phase shift nor amplification occurs. The filter can be applied to the individual station anomalies followed by computation of the difference, or applied directly to the time series of the difference anomalies with the same end result.

The smoothed anomalies of monthly sea level for each station and of sea level differences in Figures 6 and 7 were obtained by applying the

smoother eight successive times. The 50% level for the response function lies between periods of 5 and 6 months, and the response is 85% at 8 months.

CORRELATIONS BETWEEN HONOLULU-MINUS-SAN FRANCISCO AND HILO-MINUS-AVILA ANOMALIES

There are no independent data against which to check the anomalies of sea level differences as an index of nonseasonal variations in current. Since the two sets of differences span very nearly the same current region, the consistency between them is examined in this section to see if they agree reasonably well.

The correlations by month for both unsmoothed and smoothed anomalies are listed in Table 3. A general improvement of the correlations, particularly in winter, occurs as a result of smoothing to suppress the short-period variability. The effect of different scales of wind systems can be recognized by the seasonal pattern of correlations, especially in the smoothed anomalies. In the months from April through November when the subtropical high dominates the atmospheric pressure pattern over the North Pacific Ocean, all the correlations of smoothed anomalies are significant at the 1% level. In the months from November through March when meso-scale cyclonic and anticyclonic

TABLE 3.—Correlations of monthly sea level differences, by month Hilo-minus-Avila versus Honolulu-minus-San Francisco; $n = 20$ years.

Month	Unsmoothed anomalies	Smoothed anomalies
January	0.37	0.45*
February	0.37	0.44*
March	0.40	0.48*
April	0.56**	0.54**
May	0.45*	0.58**
June	0.63**	0.63**
July	0.64**	0.63**
August	0.41	0.69**
September	0.74**	0.68**
October	0.53**	0.56**
November	0.32	0.51*
December	0.57**	0.49*

* Correlation significant at 5% level ($r \geq 0.42$).
 ** Correlation significant at 1% level ($r \geq 0.54$).

wind systems move through the region, the correlations are somewhat lower, but still significant at the 5% level.

For the entire 20 years of concurrent records for Hilo-minus-Avila and Honolulu-minus-San Francisco, the correlation of unsmoothed anomalies is 0.49 and for smoothed anomalies it is 0.55. The 1% level of significance for the correlation coefficient of a sample of 240 months is 0.17, so these values are highly significant.

A visual comparison of the data in Figures 6 and 7 reveals the agreement evidenced by the correlation coefficients. Smoothed anomalies of the same sign tend to occur at the same time. For the most part the oscillations of the smoothed anomalies of sea level difference are in phase. Oscillations are noticeably out of phase in the periods October 1950-February 1951, March 1952-January 1953, September 1955-June 1956, and January-July 1958. In the last 18 months of the Hilo-minus-Avila record (July 1966-December 1967) the changes are similar to those for Honolulu-minus-San Francisco, but the smoothed anomaly of the difference is positive rather than strongly negative. Except for the 1955 periods, the nonagreement of the anomalies during these periods results mainly from a rise in sea level at San Francisco as opposed to a drop at Avila. These periods comprise only 20% of the total 20-year coincident records. In the remaining 80% the correlation coefficient for unsmoothed anomalies is 0.65 and for the smoothed anomalies it is 0.76. Both are significant well beyond the 1% level of 0.186 for a sample of 190.

CURRENT CHANGES INFERRED FROM SEA LEVEL DIFFERENCES

In this section some characteristics of the 65-year record of anomalies of sea level differences, Honolulu-minus-San Francisco are described with emphasis on their implications regarding changes in surface currents. Because the smoothed anomalies minimize local effects near the station, such as the set-up by wind and eddy systems passing near the Hawaiian Islands, they will be used as more realistic estimates of the larger scale and longer term changes in cir-

ulation. The term *current index* will be applied to this usage.

The discussion will follow the basic premise in this paper, that the currents are geostrophically related to the sea level difference so that a positive current index indicates above normal current, i.e., stronger flow to the south around the eastern limb of the anticyclonic gyre of the North Pacific Ocean. Conversely, negative current indexes indicate a below-average slope of the sea surface and proportionally weaker circulation.

Three tables have been compiled to show the characteristics of the current indexes. Table 4 gives statistical data regarding the current indexes by month. The data describe the year-to-year variations that occur. The normal monthly sea level differences, d , (of unsmoothed data) are repeated from Table 1 as a reference against which to measure the ranges and standard deviations of the current indexes.

Visual inspection of the time series (Figure 6) indicates that there are a number of different "climatic periods" in the record, i.e., periods characterized by the variability and the mean level of the current index during the period. Table 5 identifies seven such periods, into which I have subjectively divided the time series, and gives the mean and the standard deviation about that mean for each period. Obviously, other investigators might well select different climatic periods based upon other criteria related to their work.

In Table 6, highly anomalous periods have been identified on the basis of a criterion that the magnitude of the current index exceeded 10 cm for two or more consecutive months. As well as information on the dates, sign, magnitude, and duration of the current index, data are also given on the sign, magnitude, and date of the largest monthly sea level index at Honolulu and San Francisco which coincided with the current index greater than 10 cm.

Some observations which may be made about the Honolulu-minus-San Francisco differences and the information in these tables are given below.

1. The standard deviations of year-to-year changes for a given month (Table 4) vary from

TABLE 4.—Variability of current index (smoothed anomaly of sea level difference), Honolulu-minus-San Francisco, by months. $N = 65$ years. Standard deviation (s); largest positive and negative departures (Max and Min) and year of occurrence; Range (R) in centimeters and in percent of normal monthly sea level difference, $\bar{d}$ (from Table 1).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
s (cm)	5.7	6.0	6.2	6.0	5.7	5.5	5.4	5.2	5.1	5.2	5.3	5.4
Max (cm)	11.2	13.5	15.3	16.0	16.5	17.4	17.7	15.8	11.4	10.3	9.5	10.6
Year	1920	1920	1920	1920	1920	1920	1920	1920	1920	1943	1943	1948
Min (cm)	-14.7	-14.4	-13.0	-14.0	-16.1	-15.4	-14.2	-14.6	-14.5	-13.5	-13.7	-14.4
Year	1958	1958	1958	1967	1967	1967	1918	1918	1918	1918	1957	1957
R (cm)	25.9	27.9	28.4	30.1	32.6	32.7	31.9	30.4	25.9	23.8	23.2	25.0
$R/\bar{d}$, (%)	52	54	49	50	53	54	53	49	43	39	40	47
$\bar{d}$ (cm)	50.6	51.9	57.4	60.3	61.7	60.6	59.6	61.1	60.8	60.7	57.8	53.5

5.1 cm in September to 6.2 cm in March. The seasonal change is due to greater winter-time variability at San Francisco (Saur, 1962) probably caused by year-to-year differences in weather conditions. A range of two standard deviations is nearly the same as the 11 cm range of the normal seasonal cycle. Long-term non-seasonal changes exceed $\pm 10\%$ of the normal over one-third of the time.

2. The range between extremes (Table 4) in any given month varies from 23.2 cm for November to 33.7 cm in June. These are 39% and 54%, respectively, of the normal sea level differences for these months.

3. The minimum current index was -16.1 cm in May 1967 and the maximum was $+17.7$ cm in July 1920. The range between the extremes of the current index is 58% of the long-term mean sea level difference of 58 cm for Honolulu-minus-San Francisco, and it is three times as large as the range of the normal seasonal cycle.

4. The periods 1905-15, 1939-41, and 1955-69 were characterized by large changes between positive and negative values of current index over periods up to a few years, but on the average the indicated current is weaker than normal (Table 5).

5. During the periods 1915-25 and 1942-49, the current index implies moderate to large changes in current over periods of several years but indicates on the average a current stronger than normal. Except for large negative values in 1918, the current index indicates almost continuously stronger-than-normal circulation from mid-1915 through 1925.

6. The current changes during the periods 1926-38 and 1950-54 were relatively small as compared to the rest of the records. The current index did not exceed 8.5 cm and was nearly evenly distributed between negative and positive values.

7. The sea level records imply that unusually weak currents (negative anomalies in Table 6) occurred in 1911, 1918, 1941, 1957-58, and 1967, and that the periods of unusually strong currents occurred in 1915, 1920-21, 1943-44, 1948-49, and 1959.

8. During 7 of the 10 highly anomalous periods in Table 6, the absolute value of the monthly sea level anomaly at Honolulu is much larger than that at San Francisco. This indicates that significant changes in physical conditions which affect circulation occur in the central water of the current gyre as well as in the boundary current itself.

CONCLUDING REMARKS

For the investigation of historical changes in the ocean environment two notable observational deficiencies are apparent: the paucity of time-series subsurface data and the lack of information on changes in current of periods from a few months to several years. This study has attempted to develop some information on the normal seasonal cycle and the nonseasonal change of ocean currents in that part of the eastern

TABLE 5.—Mean current index, $\bar{\Delta}d$, and standard deviation, s , Honolulu-minus-San Francisco, for selected "climatic" periods (see text).

Years	Number of months	$\bar{\Delta}d$ (cm)	s (cm)
1905-14	120	-3.0	5.3
1915-25	132	3.5	6.1
1926-38	156	0.2	3.6
1939-41	36	-1.2	6.3
1942-49	96	2.6	4.8
1950-54	60	0.1	3.4
1955-69	180	-1.9	5.6

North Pacific Ocean which includes the California Current, using the most appropriate long-term records of sea level available.

Monthly sea level differences for a 65-year period (1905-69) between Honolulu and San Francisco and for 20 years (1947-59, 1961-67) between Hilo and Avila were computed to indicate the strength and fluctuations in the monthly geostrophic current around the eastern limb of the anticyclonic gyre of the North Pacific Ocean. The premise is that through the geostrophic relationship the nonseasonal variations of sea level difference indicate proportional changes in the current.

The distance between tide stations in each pair is about 3,900 km. The current structure is not uniform across the geographic region. Variability in the records is introduced by local conditions, and smoothing has been used to minimize these effects. Therefore, the sea level differences presented here can be indicative of only large-scale changes in circulation and conclusions regarding the circulation have been confined to periods of the more persistent highly anomalous periods in the sea level differences. In the tropical and western North Pacific where islands are more suitably located with respect to the currents the procedures followed here might be used to study variations in the Equatorial Currents and the Kuroshio.

In the Northeast Pacific there is no independent set of long-term observations to substantiate the inferences regarding current changes that have been drawn and no other islands for improving the network of tide stations. This lack emphasizes the desirability of frequent sections of subsurface observations between Cali-

TABLE 6.—Highly anomalous periods of sea level difference Honolulu-minus-San Francisco, 1905-69, identified by current index magnitude greater than 10 cm for at least two consecutive months.

Difference ¹	1. Sign of anomaly	2. No. of months, magnitude of anomaly >10 cm	3. Dates, magnitude of anomaly >10 cm	4. Largest anomaly, cm	5. Total months duration, anomaly of same sign	6. Inclusive dates for 5	Honolulu ¹	San Francisco ¹
	Negative	4, (1) ^a	Mar.-June 1911	-12.8	22	Jan. 1911- Oct. 1912	Negative -9.4 May 1911	Positive +4.6 Mar. 1911
	Positive	3	July-Sept. 1911	+12.9	23	May 1915- Mar. 1917	Positive +13.1 Aug. 1915	Positive +0.4 Sept. 1915
	Negative	7	1915 May-Nov.	-14.6	11	Mar. 1918- Jan. 1919	Negative -9.2 July 1918	Positive 8.6 Oct. 1918
	Positive	9, (3)	1918 Jan.-Sept. (Feb.-Apr. 1921)	+17.7, (+13.7)	30	Feb. 1919- Oct. 1925 ^b	Positive +16.6 (+11.0) July 1920, Mar. 1921	Negative -4.2, (-2.7) Mar. 1920, Mar. 1921
	Negative	3	1920 Jan.-Mar.	-13.6	23	Oct. 1940- Aug. 1942 ^c	Positive +5.0 Mar. 1941	Positive +17.7 Feb. 1941
	Positive	2, (2)	Sept.-Oct. 1943 (Jan.-Feb. 1944)	+11.2 (+11.2)	32	Sept. 1942- May 1945	Positive +10.6 (+8.5) Sept. 1943, Jan. 1944	Negative 0, -3.3 Sept. 1943, Feb. 1944
	Negative	6	Oct. 1957- Apr. 1958	-14.7	18	Apr. 1957- Sept. 1958	Negative -7.6 Nov. 1957	Positive +10.0 Feb. 1958
	Positive	2	May-June 1959	+10.3	19	Oct. 1958- Apr. 1960 ^d	Positive +9.2 June 1959	Negative -12.4 May 1967
	Negative	4	Apr. 1967- July 1967	-16.1	45	Sept. 1964- June 1968	Negative -12.4 May 1967	Positive +3.7 May 1967

¹ All data refer to the smoothed anomalies depicted in Figure 6.

^a Ignored -0.4 cm in October 1923.

^b Ignored +0.9 in June 1941.

^c Ignored -0.4 cm in October 1923.

^d Ignored +0.9 in June 1941.

fornia and Hawaii. One would like information on the strength of the California Current, on the role of upwelling in the variations of the current, about the movement of the boundary or transition zone between the central water mass and the waters of the California Current, and about the interconnection between the California Current and the North Equatorial Current. The large changes in sea level at Honolulu as compared to San Francisco during periods of strong anomalies in the sea level difference (Table 6) raise the question as to how the California Current may vary in strength or width in relation to changes in the central water mass and position of the eastern North Pacific anticyclonic current gyre. Such environmental information has important applications for advisory services and forecasting for fisheries along the west coast of the United States.

One consequence of the preliminary work with sea level differences (Saur, 1966) mentioned earlier was the start of a pilot program of expendable bathythermograph observations between Honolulu and San Francisco aboard a merchant ship (Saur and Stewart, 1967) in June 1966, which continued at a frequency of up to 20 sections per year through 1970. Although the period of observation is very short as compared to the sea level records, it is hoped that the analysis of these observations can better define conditions related to the anomalous weak circulation in 1967 inferred from the sea level records, and shed light on the more specific problems mentioned above.

ACKNOWLEDGMENTS

It is a pleasure to submit this contribution honoring Dr. O. E. Sette, a great scientist, associate for many years, and friend. This exploratory investigation of sea level differences is one outgrowth of many stimulating discussions with him on environmental variability and its implications to fisheries.

I am greatly indebted to Laurence E. Eber for encouragement and much valuable advice, including information on the smoothing procedure, and to Mrs. Dorothy D. Roll for computer pro-

gramming and assistance in data processing. Jerome Namias and Gunter R. Seckel also provided helpful suggestions.

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APPENDIX TABLE 1.—Honolulu-minus-San Francisco, 1905-69. Monthly sea level difference (linear trend removed and adjusted to normal atmospheric pressure at each station) in centimeters. The long-term mean difference for all months and years has been adjusted to 58 cm, as explained in text, by reference to 0/1,000 db geopotential heights.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1905	46.7	39.5	48.6	54.7	59.6	58.2	51.5	54.8	58.6	54.9	45.9	45.2
1906	43.8	44.1	42.1	52.9	(57.3) ¹	59.2	56.6	56.3	65.9	66.6	69.4	58.1
1907	50.2	47.1	42.3	46.8	60.5	61.5	59.6	59.6	58.9	59.0	59.4	55.1
1908	51.5	57.6	61.5	62.8	75.1	72.0	61.1	61.5	60.2	62.8	56.9	54.8
1909	38.4	39.9	56.0	59.6	53.7	51.3	56.6	54.2	50.7	49.7	52.4	41.9
1910	41.8	48.8	43.0	58.0	59.4	56.6	57.3	61.8	67.2	71.4	65.4	54.7
1911	48.0	44.7	42.6	49.7	49.2	48.5	51.7	54.7	49.3	48.0	50.4	47.6
1912	42.8	58.9	49.3	59.0	59.4	59.1	54.0	55.9	57.7	57.9	58.9	61.6
1913	52.8	55.9	66.5	62.7	65.4	64.1	60.6	52.4	54.0	59.4	56.8	55.0
1914	43.3	45.0	50.5	59.3	61.6	65.3	62.7	58.9	56.9	51.9	53.7	44.4
1915	47.2	45.7	58.2	59.9	58.2	69.2	74.2	75.5	70.4	66.5	59.2	63.6
1916	50.7	56.2	57.1	63.0	68.6	67.5	61.2	61.0	69.4	67.3	63.2	60.7
1917	55.3	57.5	60.7	51.2	62.0	66.5	64.3	64.8	61.3	63.7	62.3	57.7
1918	61.3	58.2	45.5	51.9	52.7	45.3	45.8	47.2	45.3	49.4	43.0	48.0
1919	48.5	53.2	56.9	64.3	61.4	61.6	59.8	62.2	68.4	66.8	67.3	62.8
1920	60.4	65.5	73.9	78.4	74.5	76.6	81.6	76.1	72.1	67.5	59.8	56.9
1921	53.4	68.0	68.7	76.6	69.6	68.6	59.1	65.2	67.0	59.1	62.9	57.6
1922	62.6	54.4	63.8	66.3	66.3	58.7	57.1	65.0	66.4	60.8	65.1	54.7
1923	56.3	52.3	66.9	58.8	65.1	63.2	62.2	65.6	61.0	60.8	53.3	60.5
1924	56.7	56.6	63.2	63.7	68.4	64.3	60.9	64.6	62.1	61.6	65.8	60.8
1925	63.0	56.3	55.5	63.7	62.5	64.1	64.0	65.3	61.3	62.8	58.7	51.1
1926	46.9	50.0	55.7	61.9	70.6	67.7	66.3	63.7	68.3	59.1	50.4	59.8
1927	51.0	45.4	59.3	57.3	62.5	57.1	64.7	65.5	66.9	57.5	52.6	50.5
1928	52.2	53.7	62.3	65.6	67.4	58.8	53.2	51.4	58.1	53.4	52.2	46.1
1929	49.3	55.6	58.2	56.2	60.2	59.9	57.4	60.7	58.1	62.0	56.5	58.4
1930	49.5	51.1	50.7	53.8	62.7	63.9	63.7	58.4	61.3	58.3	53.1	50.2
1931	55.7	54.8	66.2	66.5	64.3	63.0	62.8	59.8	61.0	66.5	66.4	58.9
1932	50.9	45.9	62.3	58.9	58.3	65.5	57.6	60.8	56.8	63.1	67.4	62.7
1933	58.5	59.6	60.7	68.1	71.6	64.1	61.2	61.0	64.6	67.4	62.0	57.0
1934	56.1	50.8	55.3	61.7	57.2	56.4	52.6	53.0	56.7	59.4	55.2	47.3
1935	44.2	50.8	54.7	64.6	65.0	60.1	56.0	61.6	64.4	61.4	65.3	53.7
1936	57.2	49.0	57.0	67.7	64.2	61.8	61.0	66.0	60.3	56.2	57.3	59.0
1937	58.3	48.3	46.3	65.4	59.2	55.6	52.0	60.9	60.4	65.0	56.6	42.6
1938	46.5	40.3	49.1	59.4	58.9	57.4	55.1	54.2	66.3	63.6	58.4	48.8
1939	50.7	63.1	68.0	70.3	69.2	64.5	67.7	59.1	49.7	50.5	49.5	54.6
1940	50.0	51.3	53.9	58.9	58.4	65.0	70.3	67.8	60.0	65.1	59.6	43.6
1941	39.1	38.2	43.1	56.0	62.1	67.6	51.5	59.5	55.6	51.8	50.6	47.3
1942	49.0	51.2	61.2	54.0	58.1	60.2	56.3	61.6	61.2	68.2	64.3	64.4
1943	51.1	53.7	67.7	70.2	62.3	58.9	62.2	74.7	71.4	70.4	66.1	62.3
1944	63.0	64.3	65.6	69.5	61.2	65.4	63.6	67.0	62.3	63.2	59.1	53.2
1945	59.0	59.2	65.3	67.1	64.4	58.5	54.7	55.8	55.6	54.2	58.7	52.4
1946	55.6	58.5	68.7	65.4	60.3	64.1	60.3	64.3	62.6	60.0	55.5	54.5
1947	52.5	49.2	54.4	61.9	59.8	62.5	69.3	69.3	65.9	75.3	64.4	57.9
1948	51.9	56.2	57.5	48.3	54.4	54.2	55.1	55.6	57.4	65.9	64.1	63.0
1949	66.7	57.7	61.6	64.4	63.8	55.5	58.8	60.3	56.5	61.6	57.5	55.7
1950	54.5	58.9	66.5	65.9	65.0	58.3	57.3	63.6	63.0	61.8	56.0	49.9
1951	51.3	49.4	54.8	57.0	57.3	54.5	55.0	60.2	59.1	59.7	53.7	45.2
1952	37.0	53.3	61.5	61.3	63.4	57.4	56.3	60.7	61.0	59.6	56.5	49.5
1953	41.8	57.3	60.6	60.7	64.2	61.7	62.0	69.8	58.6	61.8	57.4	59.5
1954	50.6	54.4	51.6	59.1	59.9	58.7	60.4	63.5	69.7	69.4	63.0	55.7
1955	52.1	57.2	56.5	57.1	56.6	44.0	51.6	55.8	62.2	66.9	62.9	41.3
1956	34.5	43.9	55.9	57.7	55.8	58.2	52.5	57.1	62.0	61.7	61.2	61.0
1957	58.2	54.1	60.2	59.5	53.6	57.1	54.9	57.5	50.3	46.6	44.8	39.7
1958	37.6	33.3	47.9	47.8	54.6	53.5	60.5	55.7	59.6	61.2	64.2	53.4
1959	50.8	50.7	66.7	65.4	72.5	75.2	62.9	68.1	65.0	58.6	56.2	56.7
1960	50.3	55.2	57.0	62.9	62.0	56.9	55.8	58.0	54.4	61.3	58.3	53.5
1961	49.9	53.3	58.8	65.6	66.2	68.4	69.9	68.7	70.3	69.3	55.8	50.8
1962	59.9	56.7	63.2	70.2	66.6	65.8	61.4	57.2	56.7	46.9	56.9	53.5
1963	50.8	43.7	59.7	51.8	59.9	59.4	55.9	65.1	61.8	61.0	54.7	46.2
1964	45.5	55.1	65.1	69.0	63.2	62.7	73.8	61.9	59.2	(57.6) ¹	53.2	51.1
1965	42.3	45.9	52.9	45.9	58.6	54.7	60.2	54.0	51.5	55.7	52.2	47.0
1966	46.4	50.6	59.0	54.0	52.8	56.3	59.1	61.5	60.6	56.6	51.8	51.3
1967	45.5	51.0	46.1	44.2	45.6	46.2	45.8	52.5	56.0	59.3	54.1	54.9
1968	48.7	45.4	50.9	50.7	53.9	56.8	61.1	65.3	62.6	63.7	62.3	55.6
1969	44.3	42.1	57.3	58.0	64.8	66.4	63.3	59.5	60.9	57.2	49.8	43.5
N	65	65	65	65	64	65	65	65	65	64	65	65
MEAN	50.6	51.9	57.4	60.3	61.7	60.6	59.6	61.1	60.8	60.7	57.8	53.5

¹ Missing value was estimated by interpolation of anomalies.

APPENDIX TABLE 2.—Hilo-minus-Avila, 1947-59 and 1961-67. Monthly sea level difference (linear trend removed and adjusted to normal atmospheric pressure at each station) in centimeters. The long-term mean difference for all months and years has been adjusted to 52 cm, as explained in text, by reference to 0/1,000 db geopotential heights.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1947	42.4	40.0	50.9	58.1	58.8	53.7	62.2	57.3	59.5	57.1	52.0	54.1
1948	40.8	47.9	48.5	56.0	56.7	49.2	54.4	54.9	48.7	57.2	53.6	55.9
1949	45.9	47.1	62.5	61.8	59.9	52.8	50.4	57.6	54.2	55.2	47.7	45.7
1950	46.5	48.6	60.9	63.2	55.8	54.1	46.3	51.6	51.7	54.8	56.1	55.1
1951	52.0	52.1	51.5	56.1	47.4	49.8	50.3	54.5	52.0	47.0	49.1	43.1
1952	35.7	49.2	48.3	49.7	52.6	54.3	54.2	57.5	57.4	52.7	58.8	52.1
1953	49.0	51.2	46.3	56.8	56.6	53.5	52.8	52.8	48.3	55.5	50.1	45.7
1954	47.5	44.7	48.7	55.1	51.0	58.6	53.8	54.4	61.2	55.7	54.2	45.4
1955	44.8	52.3	48.7	54.4	52.9	43.6	48.7	52.6	49.0	48.4	47.7	42.6
1956	45.0	48.8	52.7	66.2	56.9	49.4	53.4	52.3	49.8	53.1	50.0	48.3
1957	52.0	52.7	59.1	56.5	52.6	49.2	42.9	40.7	47.2	48.0	37.2	35.7
1958	40.7	47.0	54.9	59.5	53.9	58.4	53.2	50.4	49.7	48.4	49.5	46.1
1959	43.6	44.3	60.2	58.0	61.3	61.5	53.5	58.3	52.0	47.5	43.6	45.7
1960	--	--	--	--	--	--	--	--	--	--	--	--
1961	45.5	52.1	63.3	56.6	73.6	71.3	63.9	59.0	66.6	56.0	51.4	41.8
1962	50.4	46.6	58.7	65.4	53.0	48.9	47.4	46.6	46.3	44.8	49.2	43.3
1963	(39.5) ¹	38.3	43.8	49.4	55.9	57.5	53.8	60.3	55.5	53.6	47.0	40.7
1964	45.0	47.8	53.1	61.9	54.9	53.1	62.8	51.0	57.3	55.8	51.1	54.3
1965	47.9	38.8	42.8	40.9	55.7	52.6	52.0	51.7	39.1	48.0	51.1	43.1
1966	51.6	50.7	59.8	50.1	47.5	58.6	55.1	57.4	62.0	59.5	56.9	49.4
1967	47.8	50.8	51.5	56.1	54.4	47.9	53.9	57.1	53.0	59.3	54.5	51.2
N	19	20	20	20	20	20	20	20	20	20	20	20
MEAN	46.0	47.6	53.3	56.6	55.7	53.9	53.3	53.9	53.0	52.9	50.5	47.0

¹ Missing value was estimated by interpolation of anomalies.

MARINERS WEATHER Log

EXPENDABLE BATHYTHERMOGRAPH OBSERVATIONS FROM SHIPS OF OPPORTUNITY

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INTRODUCTION

Personnel of merchant and fishing vessels, who have cooperated for many years in taking and reporting weather observations, are now beginning to make observations of water temperatures below the sea surface to depths of 760 m (2,500 ft). Such observations from freighters, tankers, transports, and fishing vessels are made possible by the relatively new expendable bathythermograph, commonly called the "XBT." Oceanographers call these cooperating nonoceanographic vessels "ships of opportunity."

USES OF SUBSURFACE TEMPERATURE DATA

The primary impetus in the development of the XBT came from the U.S. Navy, whose advances in anti-submarine warfare technology required a subsurface system for recording temperatures that was more accurate and easier to use than the mechanical bathythermograph (MBT). For a dependable observation with the MBT, the ship must slow to 5 kt or less in order to lower and raise the instrument to the required depth (a maximum of 900 ft). This operation usually takes more than 20 min. With XBTs, observations can be made in a few minutes at speeds as high as 30 kt without interfering with the ship's operation.

Although the military need made the development of the XBT feasible, other oceanographic studies of the marine environment also awaited the development of instruments that would economically provide the capability of oceanographic monitoring. By this, we mean the collection of oceanographic observations widely enough distributed in time and space to reveal the week-to-week, month-to-month, and year-to-year

differences in a changing ocean. This procedure may be likened to the collection of weather observations that are used to determine storm patterns and forecast weather conditions. Such an oceanwide monitoring system will require observations from many sources, such as buoys, satellites, coastal and island stations, oceanographic research ships, and especially ships of opportunity.

Of the many variables to be observed it seems logical to start with temperature, because it is easily measured and because it is of paramount importance to the following marine biological and physical problems:

1. Marine organisms are affected both directly and indirectly by temperature. One well-known example of harmful temperature changes is the El Niño effect, which occasionally develops along the Pacific coast of South America in the general region of Peru. Here a relaxation of the upwelling of cold water from below the surface and the incursion from the north of much warmer surface water, often accompanied by the bloom of microscopic toxic organisms, cause widespread destruction of coastal fauna. The commercially abundant anchovies (anchovetta) leave the surface layers to avoid the warm water, and the guano birds that normally feed on them emigrate in search of other food or starve in large numbers.
2. Temperature is known to affect migration patterns and group behavior of marine animals. Many nekton (swimming marine organisms) prefer certain temperature ranges. When the albacore, a temperate-water tuna, migrate eastward from the central North Pacific Ocean toward the coast of North America in early

summer, they generally appear in the fishing area where surface temperatures are between 15° and 20° C (59°-68° F).

3. An example of behavior affected by temperature can be found in tropical tunas, which are often fished by purse seine. Statistical studies have shown that when the thermocline (a layer of water separating the warm surface layer from colder deeper water) becomes sharper and is shallower than the bottom of the seine, there is less chance that the tuna will escape by diving below the net before the bottom is drawn together, or "pursed." The tuna tend to avoid passing down through the thermocline.
4. The monitoring of large ocean current systems by direct measurement of currents is difficult and expensive, so oceanographers often turn to the temperature distribution from which many inferences about the circulation can be drawn. Circulation of waters in the sea, including not only horizontal ocean currents but also vertical currents, is extremely important to the inorganic chemical nutrients essential to the growth of phytoplankton (microscopic plants, the first step in the food chain in the sea). In turn, the availability of microscopic food organisms to larvae and juvenile fish, may affect the survival

and the ultimate abundance of fish spawned that year. Further, the distribution of heat in the sea, noted next, is very dependent upon the ocean currents.

5. A major physical application of the knowledge of temperature distribution and its changes is related to weather forecasting. Water has a high heat capacity so that the ocean acts as a giant heat reservoir. Not only does it store vast quantities of heat during summer for release in winter, but it may also store a fraction of the heat gained over periods of several years. This abnormal storage, as recognized by monthly temperature anomalies (differences from monthly averages), and the later release of the heat may play a significant role in the modification of large-scale weather patterns. Consequently, a knowledge of the changes in heat storage below the surface of the ocean is necessary to research into long-range weather forecasting.
6. Finally, vertical temperature gradients in the ocean have a large effect on the propagation of sound in the sea. Generally, cooling and deepening of the surface mixed layer increases the detection ranges of sonar equipment used by the Navy and fishing vessels. Conversely, warming

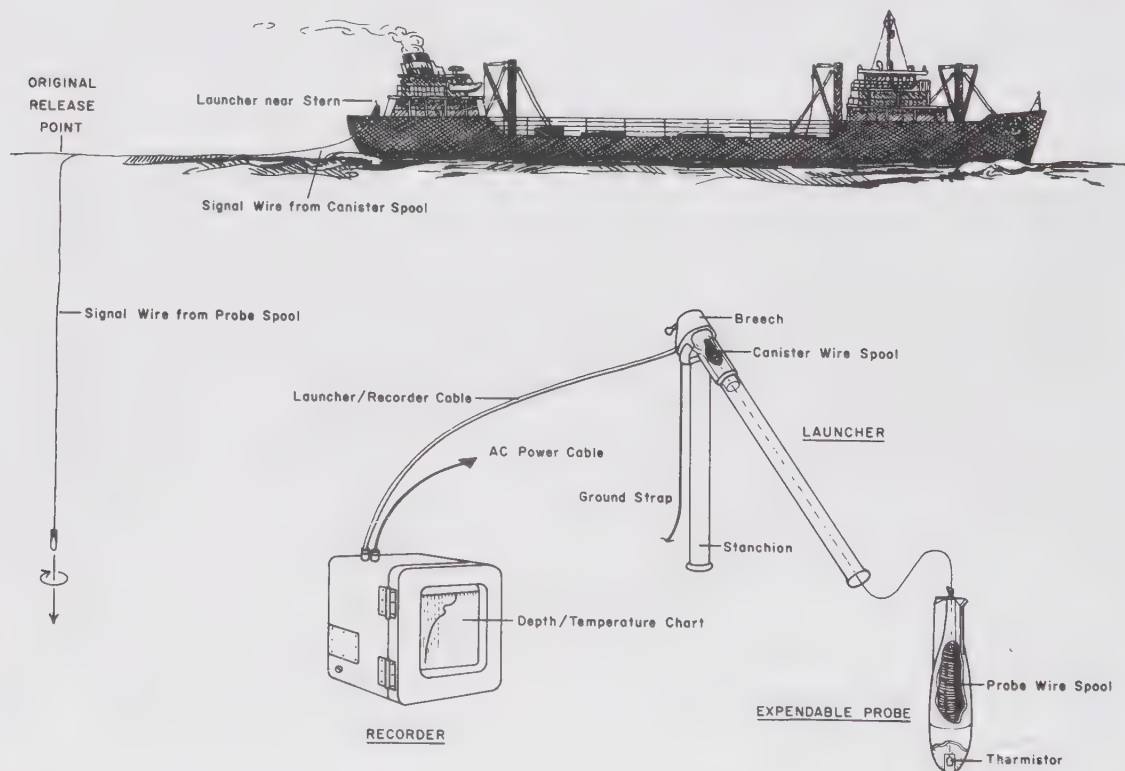


Figure 1.--The expendable bathythermograph system and its operation. Three major components of the system are the recorder, launcher, and canister containing the expendable probe and signal wire. The dual-spooling system for the signal wire permits the probe to sink vertically from its point of entry and the observation to be recorded as the ship proceeds on course.

and a decrease in the depth of the mixed layer reduces the detection ranges of hull-mounted sonar.

THE EXPENDABLE BATHYTHERMOGRAPH SYSTEM

The expendable bathythermograph system, which was engineered and developed by Sippican Corporation,* of Marion, Mass., has three major components (fig. 1). Two components, the launcher and recorder, small and light enough to be carried aboard ship by hand, are mounted semipermanently on the ship. The third and expendable component, one of which must be used for each observation, is the canister (fig. 2), which contains the expendable probe and signal wire.

The temperature sensing element is a rapid-response thermistor. It is mounted in the nose of the ballistically shaped expendable probe (fig. 1), which is about 22 cm (8.7 in.) long, 6 cm (2.4 in.) in diameter, and weighs about 700 g (under 2 lb). The dual-spooling system, see figures 1 and 2, for maintaining an electrical connection between the thermistor and shipboard recorder during the recording cycle is basic to the expendable design. As the ship proceeds on course, the fine (3.5 mm) insulated two-conductor signal wire is payed out freely on the water from the canister spool, which remains in the launcher. During the same period, the spool in the probe pays out wire freely from its finned tail and allows the probe to descend vertically from its point of entry at the surface of the ocean. The probe, which is spin stabilized and carefully weighed in manufacture, has a calibrated rate of fall, so that the depth is determined from the time interval from its entry into the water.

*Use of company name does not imply endorsement of the product by the U.S. Government.

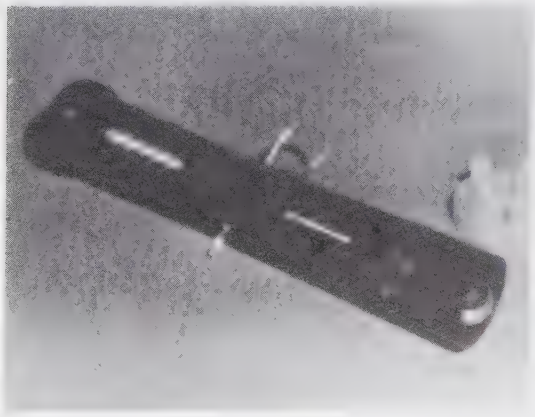


Figure 2.--Cutaway view of canister (35 cm long and 6 cm in diameter) reveals the two spools which together hold about 1.8 km (1.1 mi) of signal wire. The thermistor for sensing temperature is mounted very near the nose of the probe (at right) in the tubular opening extending along the axis of the probe. Release pin and protective cap are also shown.

The recorder operates automatically. When the release pin is pulled, the probe slides out of the launcher by gravity (fig. 3)--no explosive or propulsion device is involved--and the recording cycle is triggered by entry of the probe into the water. The temperature-depth trace is recorded as the probe descends. When the signal wire is expended, it breaks and the probe is lost. After a fixed recording period, the recorder automatically stops and returns to a standby position, ready for the next observation.

The system records over the normal range of sea temperatures, -2° to 35° C (28° - 95° F). Probes are made for two primary depth ranges: (a) to 460 m (1,500 ft) for ship's speed up to 30 kt and (b) to 760 m (2,500 ft) for ship's speed up to 15 kt. The recording cycles last 90 sec and 180 sec respectively.

OBSERVATIONAL PROCEDURES

The work aboard ship at each observational period is neither difficult nor involved.

1. The XBT system is very simple to operate. The loading of the canister into the launcher, the release of the probe, and the recording cycle take less than 4 min.
2. A reference temperature observation is taken and recorded. This observation may be a surface temperature taken with a bucket thermometer or a representative water intake tempera-

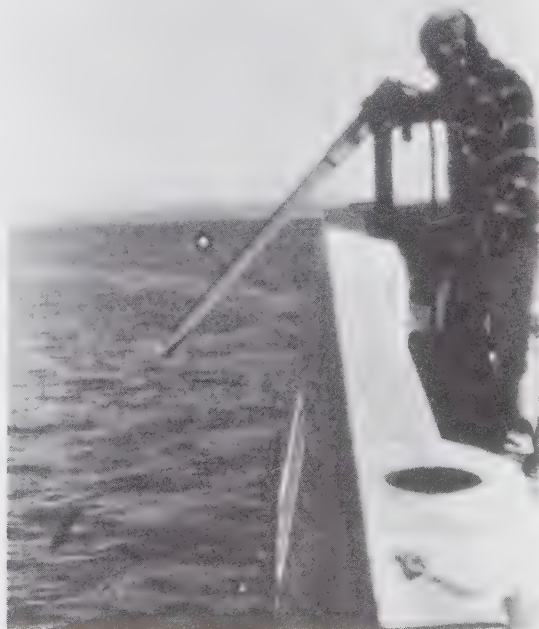


Figure 3.--A test drop of an XBT is made from the National Marine Fisheries Service research vessel, DAVID STARR JORDAN. The probe can be seen in midair at lower left, but the signal wire is so fine (3.5 mm) that it does not show up in the photograph.

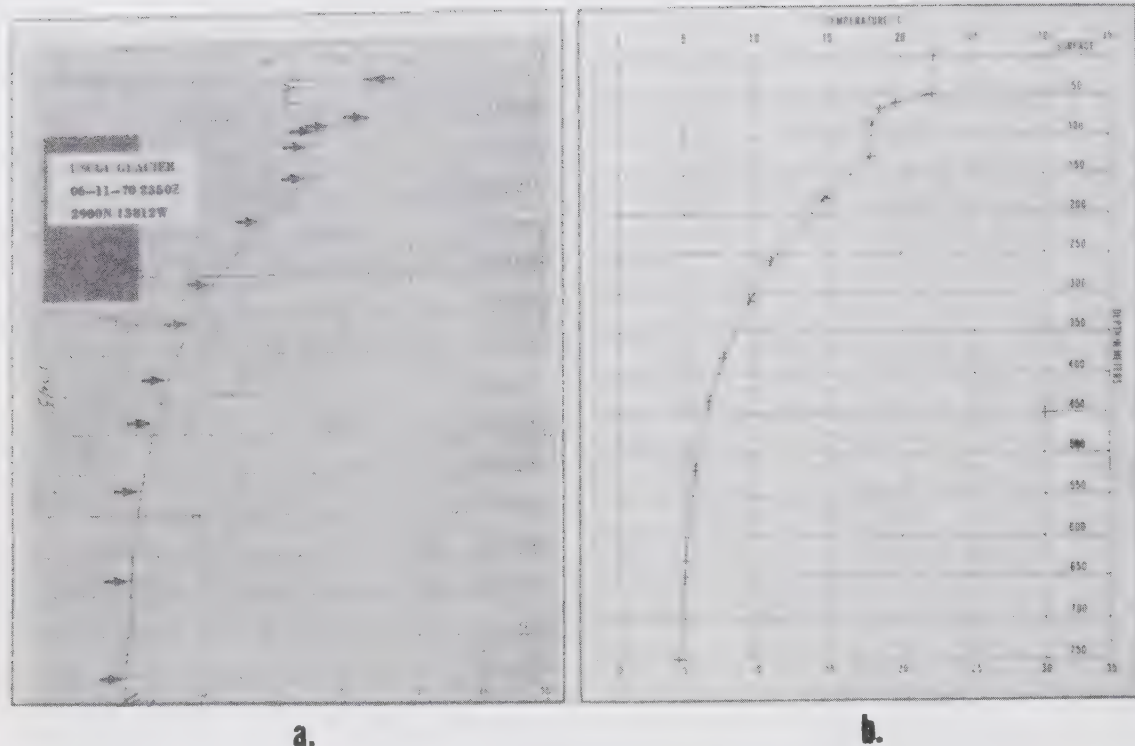


Figure 4. --An XBT observation taken in the eastern North Pacific (29.0° N., 138.2° W.). a) Original trace with arrows designating significant points and standard depths that are read and encoded into BATHY message, b) the computer reconstructs the trace by drawing straight lines between the encoded temperature-depth points.

ture from the engineroom. For the latter, it is preferable to install an accurate electronic thermometer with an easily read meter in the engineroom or on the bridge.

3. Identification information, including observation number, time, location, and reference temperature, is entered on an observation logsheet furnished to the ship for the purpose.
4. A radio message (BATHY report) is encoded by reading the depth and temperature of enough characteristic points to describe adequately the recorded trace (fig. 4). The encoded BATHY message is held until the next regular watch of the radio officer, at which time it is radioed ashore, via the Navy's Fleet Weather Centrals, for the computer analyses prepared at the Fleet Numerical Weather Central, Monterey, Calif.
5. On some ships a sample of sea water is drawn and stored for later analysis ashore to determine the salinity of the near-surface waters. The sample is generally drawn from a sea cock in the engineroom, but some bucket thermometers are designed to collect a water sample of suitable size for this purpose.

The above five steps generally take about 20 min.

On merchant ships, the general responsibility for XBT observations is usually accepted by the chief mate or the watch-standing mates. However, if ma-

rine observers of the National Weather Service are aboard to take upper air observations they will make the XBT observations. Also, under a joint program between the Maritime Administration and the National Marine Fisheries Service, cadets from the Merchant Marine Academy make the observations (see page 342 of the November 1971 issue of the Mariners Weather Log for an article describing cadet observations). The ship's captain or navigator usually takes the observation aboard fishing vessels.

COOPERATIVE OBSERVATIONAL PROGRAMS

Programs for XBT observations on ships of opportunity are almost entirely supported by separate or cooperative projects among several government agencies: the U.S. Navy, National Marine Fisheries Service, National Weather Service, and Maritime Administration.

The U.S. Navy is the major supporter. Under the cognizance of Fleet Numerical Weather Central, Monterey, XBTs have been placed aboard over 30 U.S. commercial vessels, Military Sealift Command ships, and some foreign ships (table 1) which operate primarily on transoceanic routes of the North Atlantic and North Pacific Ocean (fig. 5). Generally two or more observations per day are made under this program.

Table 1. --Ships in Fleet Numerical Weather Central's Cooperative Oceanographic Observation Program

<u>COMMERCIAL - Atlantic</u>		
Farrell Lines, Inc.	SS AFRICAN COMET SS AFRICAN CRESCENT SS AFRICAN METEOR	SS AFRICAN PLANET SS AFRICAN RAINBOW SS AFRICAN STAR
Moore-McCormack Lines, Inc.	SS MORMACALTAIR SS MORMACBAY	SS MORMACLYNX SS MORMACVEGA SS ROBIN GRAY
Prudential-Grace Lines, Inc.	SS PRUDENTIAL OCEANJET	
Transmediterranea Company	M/V VILLA de MADRID	M/V CUIDAD de SALAMANCA
<u>COMMERCIAL - Pacific</u>		
American Mail Lines, Inc.	SS ALASKA MAIL SS AMERICAN MAIL SS CANADA MAIL SS HONG KONG MAIL	SS JAPAN MAIL SS OREGON MAIL SS PHILIPPINE MAIL SS WASHINGTON MAIL
Sea/Land Lines, Inc.	SS ELIZABETHPORT SS LOS ANGELES	SS SAN FRANCISCO SS SAN JUAN
<u>MILITARY SEALIFT COMMAND</u>		
	USNS AMERICAN EXPLORER USNS FURMAN USNS MARSHFIELD USNS NORWALK	USNS SHENANDOAH USNS SHOSHONE USNS VICTORIA USNS YUKON



Figure 5. --Operating areas of cooperating ships of opportunity. Shaded areas indicate major trade routes on which ships take two to three observations per day. Solid lines show two routes where frequently repeated sections of six or more observations per day are taken to investigate time-changes in major currents. Dashed lines show routes selected for development of similar time-series during the International Decade of Ocean Exploration.

Table 2. --Fishing vessels cooperating in the Fishery-Oceanography Observation Program of the National Marine Fisheries Service, Southwest Fisheries Center, La Jolla, Calif.

TYPHOON	QUEEN MARY*
CONQUEST	MARIETTA*
J. M. MARTINAC	GINA KAREN*
SEAQUEST	KERRI M*
ANTONINA C	VIVIAN ANN*
INDEPENDENCE	LOU JEAN II*
SUNRISE**	KATHLEEN*

* XBT systems owned by vessel

** XBT system owned by Oregon Fish Commission

The Fleet Numerical Weather Central also furnishes XBT systems and probes which National Marine Fisheries Service has placed aboard fishing vessels (table 2). Most of these vessels fish for tuna off the west coast of the United States and in the eastern tropical Pacific Ocean. These vessels, which often frequent ocean areas off the normal sea lanes, take one to four observations per day. Radio reports from the fishing vessels are generally channeled to the Fleet Numerical Weather Central through the National Marine Fisheries Service radio station WWD operated at La Jolla by Scripps Institution of Oceanography.

An initial phase of a cooperative program between the Maritime Administration and National Marine Fisheries Service has recently been completed. Cadets from the Merchant Marine Academy undergoing sea training made two to four observations per day on two ships in the Pacific and eight in the Gulf of Mexico and tropical Atlantic (table 3). The routes and areas were selected to contribute information for fishery and oceanographic research projects of the National Marine Fisheries Service, which services the equipment, instructs and advises the cadets, and collects and uses the data. Cadet participation is expected to increase in the future.

The above programs have the general purpose of achieving a widespread coverage of observations throughout the oceans of the Northern Hemisphere. This broad coverage is needed for many quasi-synoptic analyses and forecasts of oceanographic conditions, which are produced every 12 hr on the computers of the Fleet Numerical Weather Central. One analysis which depends almost entirely upon temperature-depth data from XBT observations is that of surface layer depth (fig. 6). Such analyses require that the observational data are coded into BATHY messages and sent out daily by radio from the cooperating ships.

For certain research purposes, it is desirable to have more closely spaced observations, repeated regularly along the same track (time-series sections). In June 1966, the Ocean Research Laboratory, † of the former Bureau of Commercial Fisheries, Stanford, Calif., initiated such a project aboard the SS CALIFORNIAN, a bulk cargo and container vessel of Matson Navigation Company. This ship traveled reg-

†This project transferred to National Marine Fisheries Service, Southwest Fisheries Center, La Jolla, Calif., in July 1970.

Table 3. --Cooperative ships in the Joint Maritime Administration-National Marine Fisheries Service Ship of Opportunity Program

<u>Atlantic Ocean and Gulf of Mexico</u>		
Moore-McCormack Lines, Inc.	SS MORMACARGO	SS MORMACLAKE
	SS MORMACTRADE	
Prudential-Grace Lines, Inc.	SS SANTA CRUZ	SS GULF MERCHANT
	SS GULF SHIPPER	
Delta Steamship Lines	SS DELTA BRAZIL	SS DEL SUD
	SS IDAHO	
<u>Pacific Ocean</u>		
States Line	SS IDAHO	SS MICHIGAN

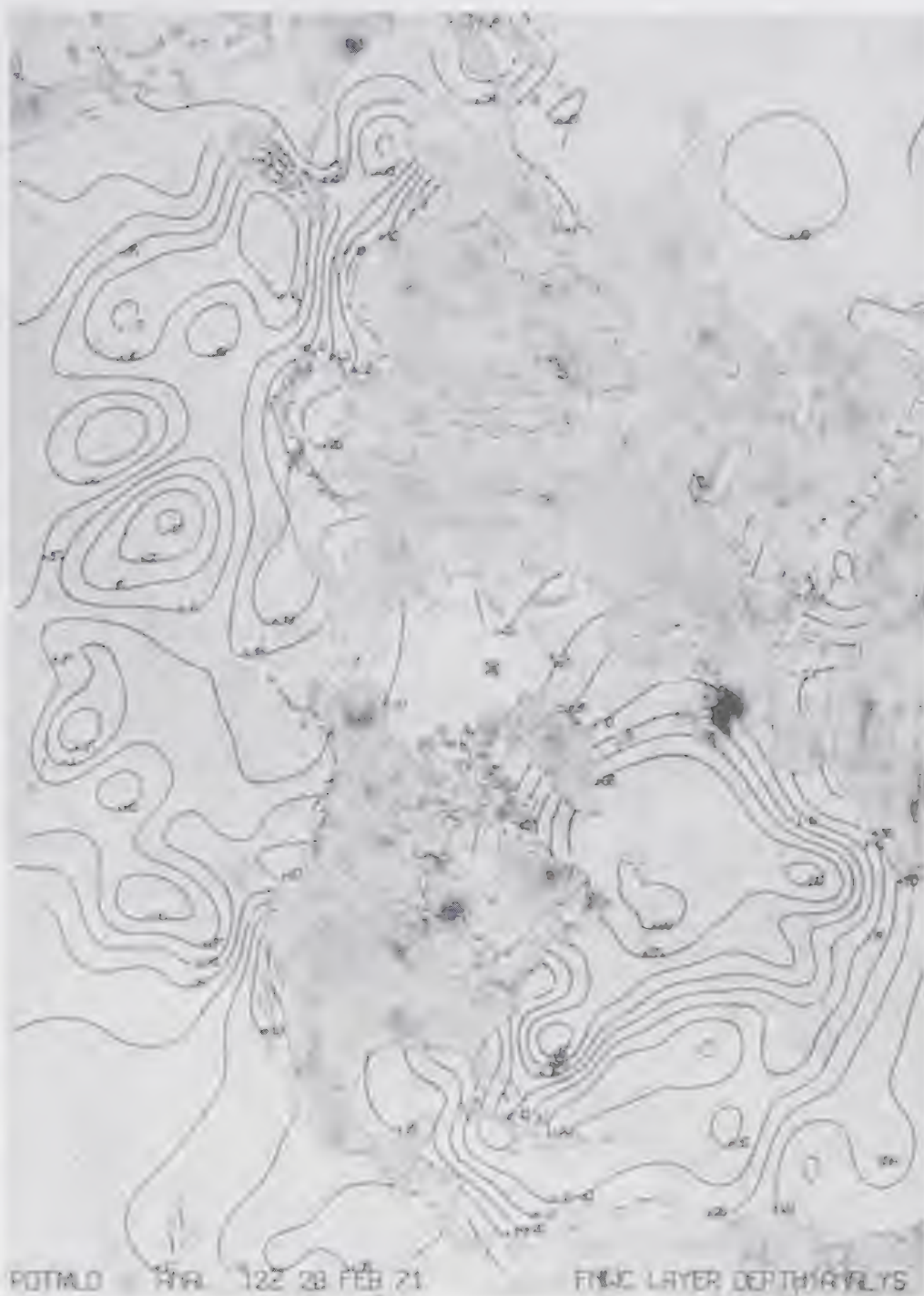


Figure 6.--Chart of layer depth (contours every 5 m [16.4 ft] starting at 20 m [65.6 ft]) is one of several oceanographic analyses produced every 12 hr by the computers at the Fleet Numerical Weather Central.

ularly between San Francisco and Honolulu (fig. 5). Up to six stations per day have provided a comprehensive 4 1/2-yr time-series (June 1966-December 1970) of subsurface temperature sections along this track, averaging about 18 to 20 days apart. The data are being used to study variations of temperature, heat content, and current in the eastern part of the major current gyre in the North Pacific Ocean, particularly the California Current. Observations have recommenced aboard another Matson ship as a part of the International Decade of Ocean Exploration (IDOE) mentioned in the next section.

The CALIFORNIAN Project exemplifies productive cooperation between a civilian agency of the Federal Government, the military, and industry. The project was initiated and supervised by National Marine Fisheries Service; electronic technology was supplied to the project, especially in the initial stage, by the Fleet Numerical Weather Central; and considerable financial support was supplied by the Oceanometrics Division of the Naval Undersea Research and Development Center, San Diego. Above all, the excellent cooperation from the shipping company and from the ship's personnel readily established the feasibility of using XBTs on merchant ships in a manner that has formed the basis for most of the cooperative programs.

Other sections of closely spaced stations have been made in the Gulf of Alaska by tankers of Chevron Shipping Company for the National Marine Fisheries Service and across the Gulf Stream on two passenger vessels (table 4) by the U.S. Naval Oceanographic Office (NAVOCEANO). Sections, from March through November 1970, which have been published in color in the NAVOCEANO monthly publication The Gulf Stream Vol. 5, No. 11, November 1970, show vividly the location and movement of the Gulf Stream.

WHAT OF THE FUTURE?

The development of a full-scale program of XBT observations from ships of opportunity is yet in its early stages. It would be necessary to put XBT systems aboard about 150 to 200 carefully selected ships to provide the minimum time-space coverage in the Northern Hemisphere oceans that would be an adequate base for synoptic oceanographic analyses by computer. Although the use of ships of opportunity is highly cost effective, limitations on funding will demand a slow and orderly growth. Emphasis should be placed on selecting ships and routes for efficient use of capital equipment and expanding observational coverage into sparse data areas. All of this will require the optimum use of ship's personnel.

As a part of the programs for the International Decade of Ocean Exploration, the National Science Foundation has granted funds to National Marine Fisheries Service to obtain time-series subsurface temperature observations on five routes in the Pacific Ocean (fig. 5). The purpose is to identify and describe seasonal and year-to-year changes of temperature and circulation in major currents of the tropical and North Pacific Ocean for further research into their underlying physical causes. Four routes radiate from Honolulu to Japan, Alaska, California, and Samoa, to provide sections across the Kuroshio, the North Pacific Current, the California Current, and the system of equatorial currents, respectively, while a route from California to Tahiti will provide an additional transequatorial section.

Those of us who have been associated with the planning and operation of past and present projects for XBT observations from ships of opportunity appreciate the excellent cooperation we have received from the shipping companies, from ship's personnel, and from fishing vessels. We fully recognize that personnel of cooperating ships will have a key role in the continuing development and success of such programs in the future.

Table 4. --Cooperative ships in programs for time-series sections of closely spaced XBT observations

<u>NATIONAL MARINE FISHERIES SERVICE</u>	
Matson Navigation Co.	SS CALIFORNIAN
Chevron Shipping Co.	SS ARIZONA STANDARD SS WASHINGTON STANDARD SS IDAHO STANDARD SS H. D. COLLIER SS J. H. MACGAREGILL
<u>U.S. NAVAL OCEANOGRAPHIC OFFICE</u>	
Cunard Line, Ltd.	RMS FRANCONIA
Greek Lines	TSS OLYMPIA

BEHAVIOR OF BLUEFIN TUNA SCHOOLS IN THE EASTERN NORTH PACIFIC OCEAN AS INFERRED FROM FISHERMEN'S LOGBOOKS, 1960-67¹

J. MICHAEL SCOTT² AND GLENN A. FLITTNER³

ABSTRACT

Fishermen's records of 8,059 purse-seine sets made on *Thunnus thynnus* (bluefin tuna) were examined for the period 1960-67. A total of 3,538 sets were identified as to school type. The majority of these sets were made within 90 miles of the beach off southern and Baja California from lat 23°N to 34°N. The region was divided into a northern and southern area on the basis of biological and oceanographic factors.

Significant differences were observed in the occurrence of the six most common school types between the northern and southern most areas of the fishery. The difference in occurrence of the jumping, boiling, and shining schools was related to the relative absence of red crabs (*Pleuroncodes planipes*) in the northern area and to differences in the foraging behavior of *T. thynnus* on baitfish and red crabs.

Differences in vulnerability to capture and catch per successful set were noted among the five most common daytime schools as well as with respect to time of day.

Purse-seine sets made with the assistance of airborne spotters had larger catches and a greater percentage success than did unassisted sets. In addition the percentage of a particular school type taken with aircraft assistance was inversely proportional to the visibility of the schools from the mast.

The existence of different school types in scombroid fishes has been noted by several authors. In 1931, Suzuki (as cited by Uda, 1933) recognized five types of skipjack tuna (*Katsuwonus pelamis*) schools in the western tropical Pacific. Kimura (1954) listed six types of skipjack tuna schools. To these Inoue (1959) added three additional types based on behavior and association of the tuna with animals and inanimate objects. Ogilvie (1949)⁴ described 10 types of tuna

schools commonly encountered in the eastern tropical Pacific. McNeely (1961) stated that the California tuna fishermen recognized several different school types for yellowfin (*Thunnus albacares*), skipjack, and bluefin tuna (*T. thynnus*). Scott (1969) described 16 different school types for the eastern Pacific tunas, listed fishermen's synonyms, and placed them into two major groups and five lesser categories on the basis of time of day, depth of occurrence, and association with other animals and floating objects.

Various attempts have been made to correlate the type of school with fishing success. Uda (1933) and Uda and Tukusi (1934) attempted to show an "index of biting" for the different school types as did Kimura (1954). Inoue (1959) correlated the percentage success of the Japanese purse seiner fleet with school types for yellowfin, skipjack, and bluefin tuna in the western tropical Pacific. Inoue's data indicated that possible differences in school size and vulnera-

¹ This work was initiated while both authors were employed in the Tuna Resources Laboratory of the Bureau of Commercial Fisheries (now the National Marine Fisheries Service, Southwest Fisheries Center) under the direction of Dr. Richard R. Whitney, then leader of the Tuna Behavior Program.

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³ Bureau of Marine Sciences, San Diego State College, San Diego, CA 92115.

⁴ Ogilvie, H. 1949. Description of various types of tuna schools, of behavior, methods of fishing and production possibilities in relation to pole and line fishing encountered in Central America. Inter-American Tropical Tuna Commission, La Jolla, Calif. 5 p. (Manuser.)

bility to capture existed among the various school types as well as between the three species.

MATERIALS AND METHODS

In order to describe the schooling behavior of *T. thynnus* in the eastern North Pacific and to relate this behavior to percentage of successful sets and catch per successful purse-seine set, California fishermen's logbooks were analyzed for the period 1960-67. Abstracts of these logs were made available through the courtesy of the Inter-American Tropical Tuna Commission.

A purse-seine set is defined as that operation in which the net is laid out around a school of fish and the bottom of the net drawn together, capturing the fish, which are then transferred to the vessel (Orange, Schaefer, and Larmie, 1957). A complete description of the fishing operation is given by McNeely (1961). For the purposes of this paper the term "school" will apply to that quantity of fish captured in a successful set of the net. No assumptions as to the configuration of the school nor the orientation of the fish within the school will be made (see Williams, 1964; Breder, 1967).

Orange, Schaefer, and Larmie (1957) made several assumptions in analyzing single set data from fishermen's logbooks, and other workers have followed (Broadhead and Orange, 1960; Whitney, 1969). These assumptions are:

1. A set of the net is made on a single school of fish.
2. Either the entire school is captured or each set captures a constant fraction of the school upon which it is made.
3. Vessel masters can estimate accurately the tonnage from individual sets of the net.

In addition, it is assumed that the schooling behavior described in ship's logs indicated the school type evident when the fish were first observed.

The average size of all schools may actually be smaller than those cited by the fishermen because small schools of 2 tons or less may be passed over by the fishermen in the hope of cap-

turing a larger school later in the day.

In regard to the second assumption, fishermen generally agree that it is extremely difficult to "cut" a tuna school with their nets; it appears to be an all-or-nothing situation. Typically a fisherman will catch $\frac{1}{4}$ ton or less when the school is missed. These fish usually are entrapped in net folds during the pursing operation and are unable to escape with the main body of the school being set upon. The constant fraction, therefore, approaches zero. That the second assumption does not hold in every case was recognized by the original proponents (Orange, Schaefer, and Larmie, 1957). We have assumed also that the fraction of fish retained in the net from a school escaping capture is the same for all school types, as well as for all times of day; these are factors which need additional study.

Fishermen identify schools to species with considerable skill, but the system of identification is difficult to describe. Their ability to judge tonnage, however, is very good after the fish are inside the net and in full view of the mastman. The airborne spotters are extremely good at estimating school size.

Bluefin net sets were defined to be: 1) all sets in which 90% or more of the total tonnage landed was *T. thynnus*, 2) all no-catch sets in which *T. thynnus* was clearly identified as the pursued species, and 3) all sets in which it could be determined from location, water temperature, date, time, and previous and later sets by the same or other boats operating nearby that it was *T. thynnus* being sought and/or captured. Using the above criteria, we determined that a minimum of 8,059 sets were made on *T. thynnus* and 65,478 tons landed by the eastern North Pacific high seas purse-seine fleet during the period 1960-67. Of these sets, 43.9% were identified in the logbooks as to school type.

All weight references in this paper are expressed in short ton units.

SCHOOLING BEHAVIOR

The terminology of school types used in this paper is that of Scott (1969) (Table 1). *T. thynnus* exhibited 13 different types of schooling

TABLE 1.—Terms used by southern California purse-seine tuna fishermen to describe various types of tuna schools and associations (from Scott, 1969).

School fish	Associated schools ¹
Surface schools ¹	Fish and mammals ¹
Breezer	Porpoise schools
Finner	Spotters
Jumper	Spinners
Boiler, foamer, smoker, or meatball	Spotters and spinners
	Whitebelly
Subsurface schools ¹	Whale schools
	Shark schools
Black spot, dark spot, brown spot, green spot, or black ball	Inanimate object association ¹
Shiner	Log school
	Bait boat
Night schools ¹	
Fireball, ardura, glow spot, white spot, or flare	
Popper	

¹ These terms are used for organization of the table and are not used by the fishermen.

behavior and 12 different combinations of these to the commercial fishermen. There were differences in frequency of occurrence, size of the schools, and vulnerability to capture between the schools (Table 2). Differences in the occurrence of the school types in the northern and southern areas of the fishery were also evident (Table 3).

In order to eliminate possible bias in analyzing school size and percentage success, all sets made

with the assistance of airborne spotters have been separated. The effects of airborne spotters on catch data will be discussed later in this paper.

Of the 13 school types observed, only 6 were recorded often enough (50 or more times) to warrant attention.

GEOGRAPHICAL VARIATION

T. thynnus is taken along the coast of Baja California and southern California from lat 23°N to 34°N. Occasionally fish are taken north of this area, especially in warm water years, but they are few, and seiner operations are severely limited by prevailing weather and sea conditions. The greatest percentage of the bluefin catch is made within 90 miles of shore near shoals, banks, reefs, and islands.

We have divided the area of the fishery into two major areas: that area north of lat 28°59'N and the area south of and including that same latitude (Figure 1). There is some biological basis for this division, as Punta Eugenia marks the northernmost extension of the Panamic fauna (Steinbeck and Ricketts, 1941). In addition, oceanographic and meteorological conditions also differ considerably. South of Punta Eugenia, an annual visitation of warm tropical

TABLE 2.—Catch statistics for 13 different bluefin school types and 4 different categories of combined schooling behavior observed.
[All purse-seine sets recording schooling behavior are included.]

School type	Total sets	Successful sets		Total catch (short tons)	Average catch per successful set (short tons)
		Number	Percent		
Breezers	1,871	870	46.5	17,043	19.6
Boilers	221	141	63.8	1,286	9.1
Jumpers	639	414	64.8	2,192	5.3
Black spots	137	61	44.5	1,475	24.2
Shiners	111	67	60.4	776	11.6
Foamers	7	5	71.4	104	20.8
Fireballs	397	293	73.8	4,423	15.1
Fanners	7	5	71.4	45	9.0
Log	1	0	0	0	0
Whales	15	6	40.0	91	15.2
Poppers	8	6	75.0	29	4.8
White spots	7	6	85.7	58	9.7
Meatballs	3	2	66.7	40	20.0
Combined schooling behavior recorded for the following					
Breezers	96	45	46.9	837	18.6
Boilers	4	3	75.0	68	22.7
Jumpers	10	8	80.0	68	8.5
Black spots	4	2	50.0	38	19.0
Total	3,538	1,934	54.7	28,573	14.8

TABLE 3.—Catch statistics for all non-aircraft assisted bluefin purse-seine sets recording schooling behavior.

School type	North of lat 28°59'N					South of lat 28°59'N					Northern and southern areas combined				
	Total sets	Successful sets		Catch per successful set (short tons)		Total sets	Successful sets		Catch per successful set (short tons)		Total sets	Successful sets		Catch per successful set (short tons)	
		Number	Percent	Median	Range		Number	Percent	Median	Range		Number	Percent	Median	Range
Breezers	475	206	43.4	10.5	0.3-100.0	1,037	492	47.5	14.0	0.5-145.0	1,512	698	46.1	12.0	0.3-145.0
Boilers	191	114	59.7	4.0	0.3-73.0	13	7	53.9	25.0	4.0-106.0	204	121	59.3	4.0	0.3-106.0
Jumpers	572	363	63.5	2.0	0.2-25.0	23	16	69.6	5.0	1.0-44.0	595	379	63.7	2.0	0.2-85.0
Black spots	17	5	29.4	9.0	4.0-30.0	70	31	44.3	15.0	2.0-200.0	87	36	41.4	15.0	2.0-200.0
Shiners	39	29	74.4	8.0	1.0-35.0	28	10	35.7	5.0	1.0-15.0	67	39	58.2	7.0	1.0-55.0
Fireballs	296	220	74.3	8.0	5.0-140.0	94	68	72.3	12.0	0.3-65.0	390	288	73.9	9.0	0.3-140.0
Total	1,590	937	58.9			1,265	624	49.3			2,855	1,561	54.1		

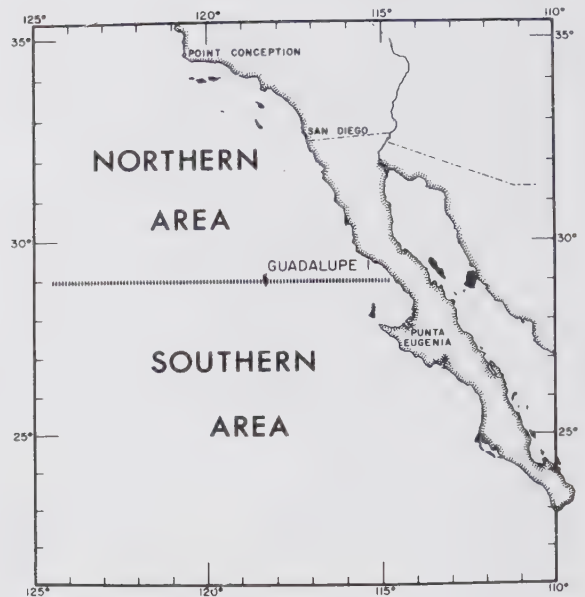


FIGURE 1.—Area of the eastern north Pacific bluefin tuna fishery.

waters occurs (except for a narrow band of very cold, rich upwelled water near shore south to San Juanico). Red crabs (*Pleuroncodes planipes*) are abundant in this area. Winds and weather are generally favorable for purse-seine operations after mid-June, but in April and May strong northwest winds severely restrict fishing.

From Punta Eugenia to Point Conception, the southern California offshore area typically exhibits the warm Catalina Gyre in association with cold, upwelled water centered off Ensenada and to the north of Point Conception. Hydrographic conditions in this region favor good filter feeding for bait fishes, and winds and weather improve in late July through September. Seldom is this district too warm for bluefin.

The occurrence of the various school types in the northern and southern areas of the fishery is nonrandom (chi square 985.20, $P < 0.001$). Perhaps the most striking difference is the almost complete lack of jumping and boiling schools in the southern area and the predominance of breezers in this same area (Table 3). These differences may reflect differences in the feeding behavior of *T. thynnus* on different prey

species. McHugh (1952) and Alverson (1963) found differences in the stomach contents of albacore, yellowfin, and skipjack tuna in different geographical areas. McHugh noted that red crabs were the dominant food item for albacore off the Baja California coast, while anchovies and other baitfish dominated in fish stomachs taken from southern California waters. Blunt (1958) noted that of 168 *T. thynnus* taken off California in 1957, 70% had been feeding on anchovies. Longhurst (1967) observed that during normal years the distribution of *P. planipes* reaches from the area of Cedros Island south, while the range extends farther north during warm water years. This distributional pattern includes the entire area from which jumpers and boilers were almost entirely absent. While baitfish, like anchovies, are found in the southern area, previously cited studies indicate that red crabs may be the preferred food item. Since *P. planipes* is a relatively weak swimmer and occurs in very dense concentrations off southern Baja California, a modified filter feeding such as Sette (1950) described for Atlantic mackerel (*Scomber scombrus*) might be employed by *T. thynnus* while feeding on red crabs. On the other hand, the vigorous pursuit by scombroids feeding on forage fish is well known (Magnuson, 1963; Whitney, 1969).

The lack of jumping and boiling schools in the southern area also may be due to differences in the behavior of *T. thynnus* feeding on *P. planipes* and baitfish and a preference for the former when available. Comparisons of stomach contents of *T. thynnus* from the three school types would provide the necessary test of this hypothesis, but such information is not available. However, analyses of stomach contents for yellowfin from an area in which *P. planipes* was the dominant food item and from a second area in which fish were the dominant item have been made (Alverson, 1963). Yellowfin sets, which were from these same two areas (but at different times in 1965) and which were identified as to school type, showed significant differences (chi square 17.27, $P < 0.01$) in the occurrence of jumping, boiling, and breezing schools (Table 4). Greater numbers of jumping and boiling schools and reduced numbers of breezers occurred in the

TABLE 4.—Comparison of breezing, jumping, and boiling yellowfin schools from the Gulf of Guayaquil and Baja California.¹

Area	Breezers		Boilers		Jumpers	
	Number	Percent	Number	Percent	Number	Percent
Baja California ²	183	91.5	1	0.5	16	8.0
Gulf of Guayaquil ³	121	77.1	11	7.0	25	15.9
Total	304		12		41	

¹ Schooling data are for 1965 (Inter-American Tropical Tuna Commission, unpublished data).

² Stomach contents: fish, 19.4%; red crabs, 78.1% (Alverson, 1963)

³ Stomach contents: fish, 76.9%; red crabs, 0.0% (Alverson, 1963)
red crabs do not occur in the Gulf of Guayaquil.

area in which fish were the dominant food item, whereas the opposite was true in the area where red crabs were the dominant item. This lends support to our hypothesis that these school types reflect behavioral differences in the feeding patterns of *T. thynnus* and other tunas on red crabs and baitfish.

If, in fact, many of the breezing schools in the southern area of the fishery are feeding upon red crabs, one would expect to find a greater percentage of successful sets on breezing schools in this area when compared with breezing schools taken in the northern area of the fishery. However the observed differences are not significant (chi square 2.18, $P > 0.20$). It might be that if feeding breezers and nonfeeding breezers were compared that differences in percentage success between the two areas would be found.

The greater number of fireball schools observed in the northern area of the fishery may reflect a difference in the distribution of bioluminescent organisms. However, persistent stratus overcast in the southern California offshore zone during summer results from upwelled water coursing southward from Point Conception. As a result of this stratus overcast, the fishermen's ability to see fireballs at night may be significantly enhanced by eliminating background illumination from the moon and stars. The phenomenon requires further study.

VULNERABILITY TO CAPTURE

There were significant differences in vulnerability to capture, as indicated by percentage of successful sets (Table 2), among the five most common daytime schools (chi square 62.32,

$P < 0.001$). These differences in vulnerability are most likely related to behavioral differences which affect a school's ability to avoid capture. Other factors such as water clarity, depth of thermocline, and water temperature also may be important. Two of the three most vulnerable school types were jumpers and boilers, both of which can be described as violently active schools in which individual fish are often in pursuit of baitfish. Shiner schools were also highly vulnerable to capture, yielding success rates of over 58%. It may be that shiners are subsurface feeding schools in which the "shines" are reflections of the operculum or of the lateral or ventral surfaces of the fish as they twist and turn in pursuit of their prey (Scott, 1969).

Three factors may be responsible for the greater vulnerability of these "feeding" schools: 1) feeding schools lack the organization of non-feeding schools; 2) individual fish in feeding schools are less aware of threatening stimuli than are nonfeeding fish, and 3) feeding schools are more likely to remain in a localized area. The first two factors would increase a school's vulnerability to capture by delaying the time at which the fish are aware of potential danger and also by increasing the elapsed time before the fish react as a unit to this danger. The third factor would make it easier for the fisherman to anticipate the position of the school when he sets upon it. Another factor which should be mentioned is that a greater percentage of actively feeding schools may be located in areas of upwelling where cold, nutrient-laden waters generally result in decreased visibility. The effect of water clarity on percentage success has been discussed by Hester and Taylor (1965).

Breezing schools are generally schools moving in a single direction, often making sudden changes in depth, which makes it difficult for fishermen to anticipate the position of the school relative to the boat before setting. Greater cohesiveness is apparent among breezing schools, and it appears that there is a greater awareness of potential danger than in feeding schools.

Blackspots are subsurface schools which are difficult to locate and to catch. The very nature of this school type suggests that a greater number of them might be expected to be found in

areas with a deep thermocline and clear surface waters. Green (1967) has shown that schools encountered in areas with a deep thermocline are less vulnerable to capture than are schools found in areas with a shallow thermocline. In addition, the deeper a school is in the water column, the closer it is to one possible route of escape: the bottom of the net. All of these factors would contribute to the greater rate of escapement observed for black spots.

We have omitted from this section any consideration of fireball schools. The reasons for the greater vulnerability of nighttime schools (discussed in a later section) are equally applicable to fireballs.

CATCH PER SUCCESSFUL SET

There were significant differences in the mean size of the six most common schools (Figure 2). Black spots and breezers were the two largest school types. The three feeding school types, jumpers, boilers, and shiners, were the smallest. The disruption of schooling behavior during feeding activity (Magnuson, 1963; Whitney,

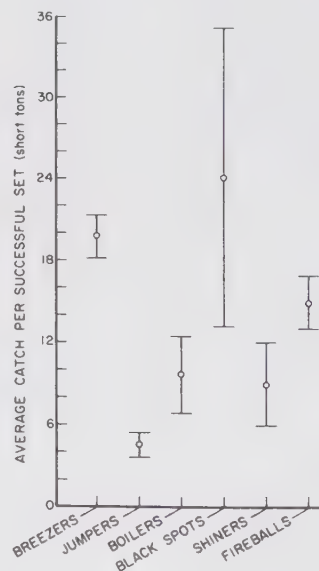


FIGURE 2.—Average catch (short tons) of each of the six most common bluefin tuna school types.

1969) may account, in part, for the reduced size of these schools. However, the observed disruptions have occurred within a relatively small area and were in response to an immediately available food source. It seems unlikely that the area involved would exceed that area normally encircled by a purse seine. We believe that the reduced size of the actively feeding daytime schools is the result of the relatively larger nighttime schools separating into smaller foraging schools with the rapid onset of higher light intensities at dawn.

Various mathematical treatments have shown the advantages of schooling to predator and prey alike (Brock and Riffenburgh, 1960; Olson, 1964). Olson contends that the swept path of an individual predator, and hence its chances of encountering a prey species, would be greatly increased if it traveled in a school rather than singly. In addition, we suggest that there is an optimum school size (number of individuals within the school) for feeding. Beyond this size, there may be increasing duplication of individual visual fields, making it more efficient for the fish to break down into a number of smaller schools in order to increase the area covered and thereby increase their chances of encountering and capturing prey. It may be also that individuals in schools beyond a certain size obtain less energy than those foraging in smaller schools. This school size would be dictated by a number of factors, such as visual acuity of the predator, type of prey, and prey density. A patchy distribution of a relatively fast moving schooling prey (e.g., anchovies) and a relatively uniform distribution of a slow moving prey (e.g., red crabs) within a localized area require different hunting and feeding strategies. Other factors may also be important (see Shaw, 1962; Breder, 1967).

TIME OF DAY

Fishermen recorded time of day for a total of 4,925 sets. Of these, 4,144 were made without aircraft assistance. The number of sets varied with time of day (Figure 3), as did the catch per successful set (Figure 4), percentage of suc-

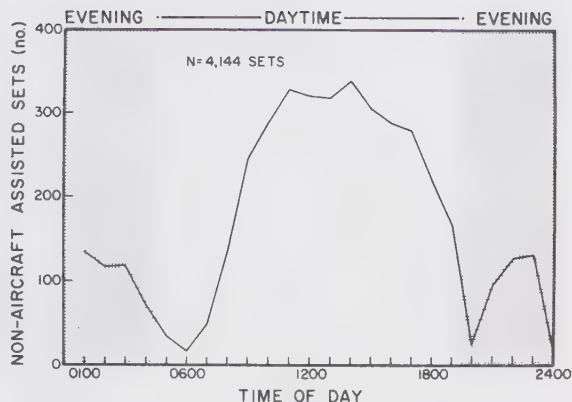


FIGURE 3.—Variation of the number of purse-seine sets on bluefin tuna in relation to time of day.

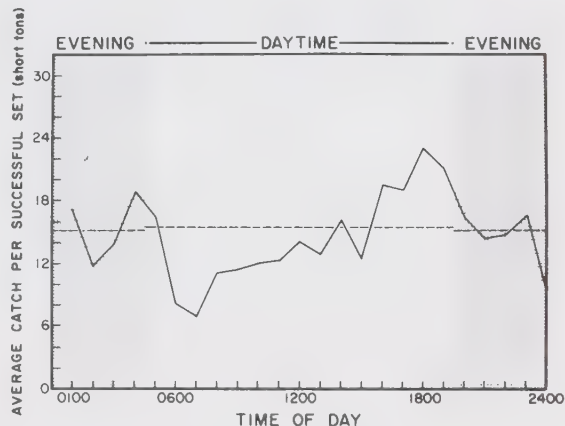


FIGURE 4.—Average catch per successful purse-seine set (short tons) on bluefin tuna in relation to time of day. (Not assisted by aircraft. Grand average catch for daylight and evening hours is indicated by the dashed lines.)

cessful sets (Figure 5), and occurrence of the various school types (Figure 6).

The percentage of successful sets on bluefin schools was significantly greater during the evening hours than it was during the day (chi square 126.56, $P < 0.001$).

Whitney (1969) suggested that the greater vulnerability of tuna to capture at night was due to decreased visibility of the net and decreased activity of the fish. Recent laboratory work using *Engraulis mordax* has shown a diel rhythm

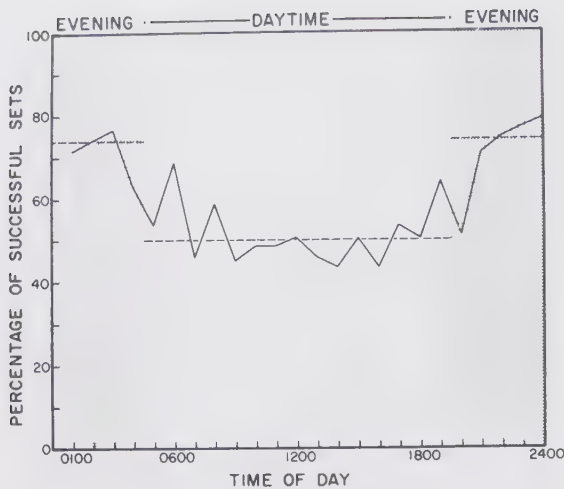


FIGURE 5.—Variation of percentage success of purse-seine sets on bluefin tuna in relation to time of day. (The grand average percentage success for daylight and evening hours is indicated by the dashed lines.)

in their direction of escape from a net cylinder (Scott, 1970). The tendency of *E. mordax* to use the bottom escape route during the day and to be random in their direction of escape at night would increase their vulnerability to capture at night by bottom-closing nets. If this same pattern is found in *T. thynnus* and other tunas, it would help to explain the observed differences in percentage success.

There were significant differences also in percentage success during the daylight hours (chi square 37.12, $P < 0.01$). This is in contrast to the lack of significant variation in percentage success during the day reported by Whitney (1969).

The distribution in time of the five most common daytime school types is nonrandom (chi square 259.15, $P < 0.001$). The three actively feeding schools were most common from 0700 to 1100 (Figure 6). During this period, these school types account for more than 42.2% of the identified school types.

The greater number of feeding schools in the early morning hours reflected in an increased percentage success during the early morning hours (0500-0800) when all school types are combined (Figure 5). The decrease in percent-

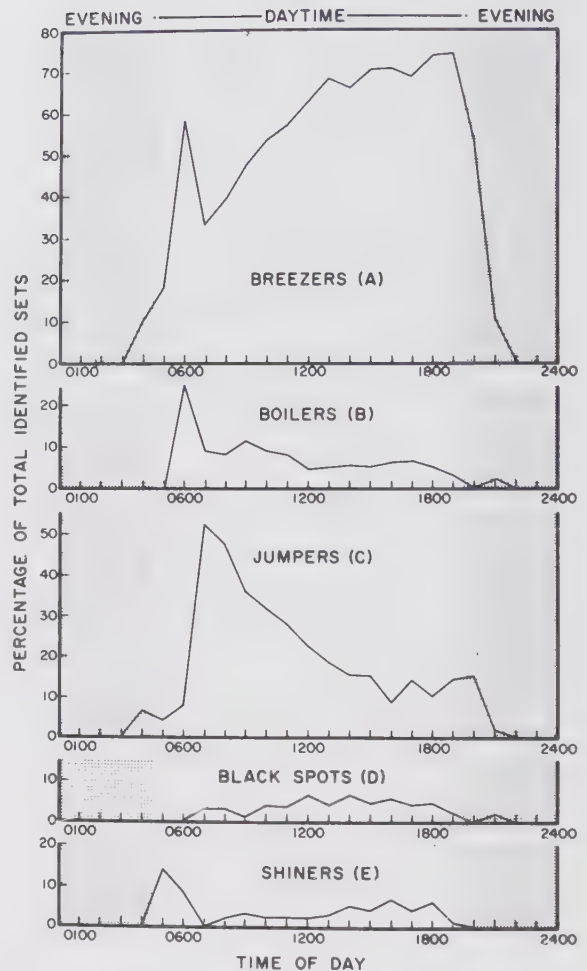


FIGURE 6.—Variation of occurrence of the five most common bluefin tuna school types in relation to time of day.

age success at 0700 is accounted for by a decrease in the percentage success of nonfeeding schools rather than a decrease in the number of feeding schools or a decrease in the vulnerability of feeding schools to capture. While the number of feeding schools increases until 1100, this is not reflected in an increase in the overall percentage success because of an accompanying increase in the number of nonfeeding schools (Figure 6). There appears to be a slight increase in the percentage of feeding schools during the late afternoon hours (1600-1900) (Figure 6B,C,D) which suggests that there may be two peaks in feeding

activity for *T. thynnus*, as has been shown for albacore (Iversen, 1962), bonito (Suyehiro, 1938), and yellowfin tuna (Uda, 1940; Waldron and King, 1963). However, the late afternoon increase in feeding activity is a minor one.

The percentage success does not vary significantly with respect to time of day in the four most common school types: breezers, jumpers, boilers, and fireballs (Figure 7). However, there is an increase in percentage success during the late afternoon hours for the three daytime schools, suggesting that the observed increase in percentage success during the late afternoon hours is due to the environmental factors cited by Whitney (1969). Additional data are needed for the late afternoon hours in order to further clarify this question.

The differences in school size between daytime (14.8 tons) and nighttime sets (14.4 tons) were not significant. However, there were differences noted in distribution of sets by 5-ton intervals (chi square 18.80, $P < 0.05$) with fewer small schools (5 tons or less) being taken at night. The reduced percentage of small schools could be the result of a greater number of these schools being passed up by the fishermen at night, possibly because of reduced visibility to the mastman. We have no evidence to suggest a real decrease in the number of small schools during night hours as opposed to daytime.

There was a marked variation in average school size within the daylight hours; the size of schools steadily increased from 6.9 tons at 0700 to 22.5 tons at 1800 hours (Figure 5). This pattern is not apparent in the jumping and boiling schools, however (Figure 8).

The early morning decrease in school size initially may be a response to increased light and feeding activity as suggested by Whitney (1969); subsequently the relatively large nighttime schools break down into several smaller foraging schools and begin their search for food. The time elapsed between the reduction in school size and subsequent occurrence of large numbers of feeding schools might thus be the time required to encounter prey and begin to feed. We believe that the reduction in the number of feeding schools after 1100 hours reflects an increasing number of fish whose hunger is sated.

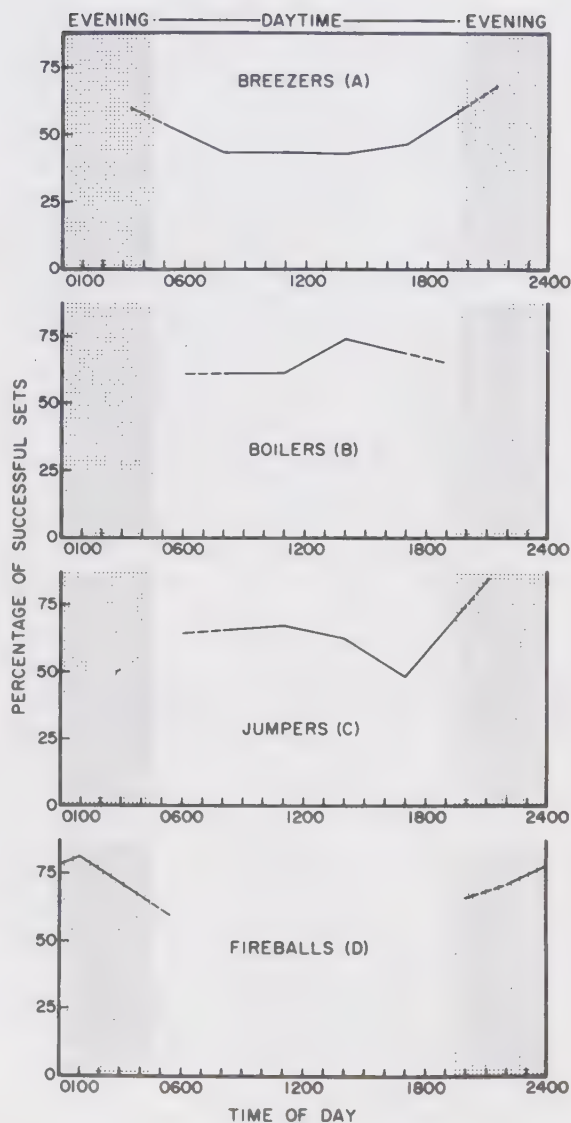


FIGURE 7.—Variations of percentage success on the four most common bluefin tuna school types in relation to time of day.

The gradual increase in school size during the daylight hours may be due to regrouping of the smaller schools through random encounters as suggested by Whitney (1969). The reduction in school size in the late afternoon cannot be accounted for by an increase in the number of

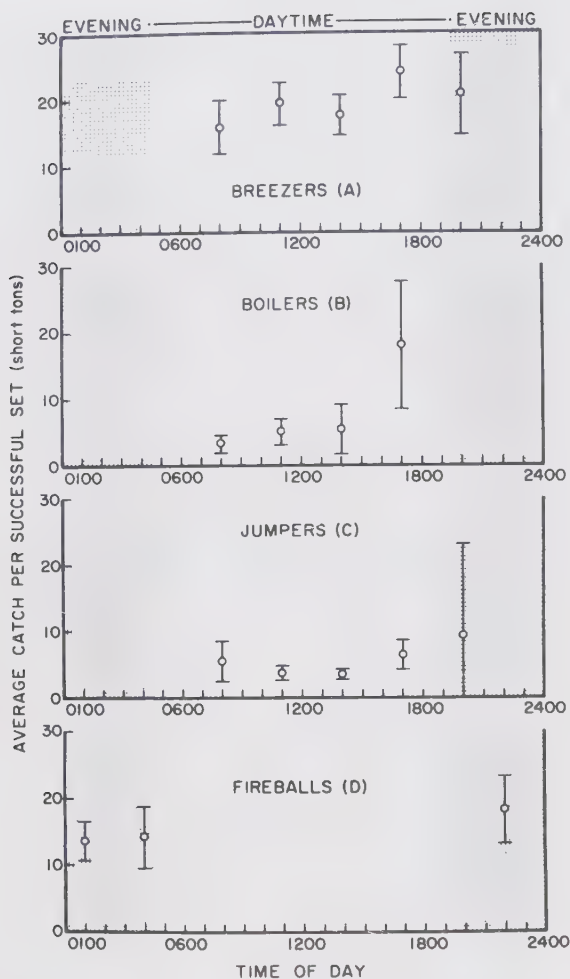


FIGURE 8.—Variation in the average catch per successful set on the four most common bluefin tuna school types in relation to time of day. (Catch in short tons grouped by 3-hr intervals.)

feeding schools and is most likely due to a reduction in available light (Whitney, 1969).

The lack of significant variation in either percentage success or catch per successful set within a single school type suggests that the observed variations in these two factors when all school types are considered together is due more to differences in the occurrence of the various school types within the daylight hours than it is to environmental factors such as daylight. However, the increased vulnerability of breezing and jumping schools during the late afternoon hours may be due to reduced light intensity during that period. Unfortunately it is the early morning and late afternoon hours for which we have the fewest data.

EFFECT OF AIRCRAFT ASSISTANCE

Aircraft assistance on bluefin tuna sets gave a significantly greater percentage of success than unassisted sets (chi square 8.69, $P < 0.01$). The average catch in assisted sets also was consistently larger than in unassisted sets (Table 5). These differences have also been shown for yellowfin and skipjack tuna. The reasons for the greater size and vulnerability of schools set upon with aircraft assistance have been discussed elsewhere (Schaefer, 1962). In addition, however, the greater average size of assisted sets may be due to the disproportionately fewer small schools (jumpers and boilers) and a greater number of large schools (black spots and shiners) captured with aircraft assistance.

The two most visible schools, jumpers and boilers, have the smallest percentage of assisted sets (Table 6). The greater height of the air-

TABLE 5.—Effect of aircraft assistance on purse-seine sets for bluefin tuna, 1960-67.

Year	Percentage of sets assisted by aircraft	Percentage success		Catch per successful set (short tons)	
		Assisted	Unassisted	Assisted	Unassisted
1960	2.5	75.0	47.3	65.7	29.3
1961	14.5	79.0	63.8	17.7	12.6
1962	12.6	72.2	65.7	17.1	9.8
1963	20.4	45.8	41.2	20.5	21.2
1964	12.1	62.8	59.5	13.3	9.3
1965	20.2	43.4	48.0	19.3	14.7
1966	13.9	60.5	46.6	22.5	15.9
1967	11.5	51.5	43.1	23.6	19.5
Average	15.3	54.9	53.0	19.3	14.2

TABLE 6.—Comparison of effectiveness of aircraft assistance by school type for purse-seine sets on bluefin tuna, 1960-67.

School type	Number of sets	Aircraft assisted sets	
		Number	Percent
Boilers	221	17	7.7
Jumpers	639	44	6.9
Breezers	1,871	359	19.2
Shiners	111	44	39.6
Black spots	137	50	36.5
Totals	2,979	514	17.3

TABLE 7.—Comparison of average catch per successful set and percentage success for assisted and unassisted sets on the four most common daytime bluefin tuna school types.

School type	Average catch per successful set (short tons)		Percentage success	
	Assisted	Unassisted	Assisted	Unassisted
Jumpers	29.1	4.7	87.5	63.7
Breezers	21.3	19.8	47.9	46.2
Shiners	15.2	9.0	63.6	58.2
Black spots	23.0	25.0	50.0	41.4

craft and, therefore, the greater area and depth of visibility to an airborne spotter would increase the possibility of spotting the subsurface schools which otherwise might not be visible to observers aboard a vessel (Green, 1966).

However, there are differences in both catch per successful set and percentage success between assisted and unassisted sets in the same school type (Table 7). All of the schools show increased percentage success with aircraft assistance, and all but black spots exhibit larger school size with aircraft assistance. This indicates that the larger size and greater vulnerability of schools set on with aircraft assistance is the result not only of the unequal distribution of the various school types between assisted and unassisted sets but also due to the skill of the airborne spotter in locating larger schools, and by his ability to increase the ship's chances of capturing the school.

MULTIPLE SCHOOLING CHARACTERISTICS

Almost every possible combination of the 13 different school types occurred. However, schools recorded as showing two or more behav-

ioral types made up a very small percentage of the total sets made. Whether this is indicative of the actual occurrence of these types or the propensity of the fishermen to record them and the log abstractor to copy them is unknown. The problem of multiple schooling types has been discussed elsewhere (Scott, 1969).

Bluefin were captured in sets with yellowfin, skipjack, and albacore. Bluefin were also observed schooling with whales (Table 1). In spite of large amounts of flotsam and jetsam occurring in the fishing area, only two reports of this school type were logged. No porpoise-associated schools were reported. This is probably due to the absence of porpoise in the areas in which bluefin are generally found. Further data are needed before meaningful conclusions can be drawn with respect to the occurrence or lack of porpoise-associated schools in the bluefin fishery.

DISCUSSION

Striking differences in catchability, size, and geographical distribution have been demonstrated for the various types of bluefin schools. Suggestions as to possible reasons for these differences are offered but in most instances additional behavioral information is needed. We hope that definitive field and laboratory behavioral studies will be made in order to further strengthen or disprove interpretations which we have drawn from the logbook data. Studies on other scombroids would also be valuable for comparative purposes. The possibility that there are two or more types of breezing schools should be studied in detail, and the percentage success of sets on breezing schools known to be feeding compared with nonfeeding schools should also be investigated.

ACKNOWLEDGMENTS

The logbook records of California tuna purse seiners were made available through the courtesy of the Inter-American Tropical Tuna Commission under Dr. J. L. Kask, Director, and Dr. James Joseph, who succeeded him. Craig J. Orange, of the Commission, provided assistance

and counsel. Dr. Richard R. Whitney originally suggested this study to us, and Dr. John R. Hunter gave valuable advice during the study. Roger E. Green assisted in constructing the original ADP format for data analysis. Dr. Richard Whitney, Dr. John R. Hunter, and Craig J. Orange reviewed the manuscript.

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THE INCREASE IN SPAWNING BIOMASS OF NORTHERN ANCHOVY, *ENGRAULIS MORDAX*

PAUL E. SMITH¹

ABSTRACT

The northern anchovy, *Engraulis mordax*, is a common fish off the west coast of North America. Its biomass has increased markedly since 1951. The various methods of deriving anchovy spawner biomass from the sardine spawner biomass and analogous census estimates of sardine and anchovy larvae are reviewed. A new compilation of anchovy and sardine larval data is presented for 1940, 1941, 1949, 1950, and 1951-69. The effect of several errors of estimate are examined and it is concluded that none is important enough to affect measurably the trend of increase between 1951 and 1966. Lastly, a current interpretation of the larval survey data is used to estimate the spawning biomass of both sardine and anchovy.

The northern anchovy (*Engraulis mordax* Girard) is a common pelagic schooling fish off the west coast of North America between British Columbia and Baja California (lat 53°N to 22°N). The fishery for northern anchovy has usually been small relative to the Pacific sardine (*Sardinops caerulea* (Girard)) off California but the anchovy catch has been increasing since the late 1930's (Figure 1). Following the collapse of the sardine fishery in the early 1950's, the catch of anchovy exceeded that of sardine. The further decline of sardine catch and the eventual moratorium on sardine, combined with a limited reduction fishery on anchovy, have again allowed the anchovy fishery to exceed that of sardine since the mid-1960's (Messersmith and Associates, 1969).

Routine planktonic larva sampling since 1951 shows an increase in the number of anchovy larvae (Murphy, 1966; Ahlstrom, 1966, 1968) and the present consensus estimate of the spawning population of northern anchovy is about 5 million tons for 1966, the last year for which complete data are available. The same sample data for the Pacific sardine now indicate an extremely small number of larvae and the spawning bio-

mass of the northern subpopulation of the sardine may now be less than 5,000 tons. All anchovy biomass estimates must now be referred to analogous sardine biomass estimates based on the sardine fishery and on sardine and anchovy egg and larva surveys because no fishery-based estimate of anchovy biomass has yet been made: this becomes increasingly difficult and imprecise as the sardine "reference" population diminishes.

The purposes of this paper are to:

- 1) review the estimates of spawner biomass of the anchovy;
- 2) present a summary of the incidence of larval anchovy by region and season since 1951;
- 3) examine the effects of three spawning behavior models on the estimates of spawning biomass;
- 4) establish a standard reference period for the determination of anchovy biomass without further consideration of the current size of the sardine population.

PREVIOUS ESTIMATES OF ANCHOVY BIOMASS

Messersmith and Associates (1969, p. 9) tabulated all the estimates of anchovy spawning biomass for the years 1940-66. Ahlstrom (MRC,

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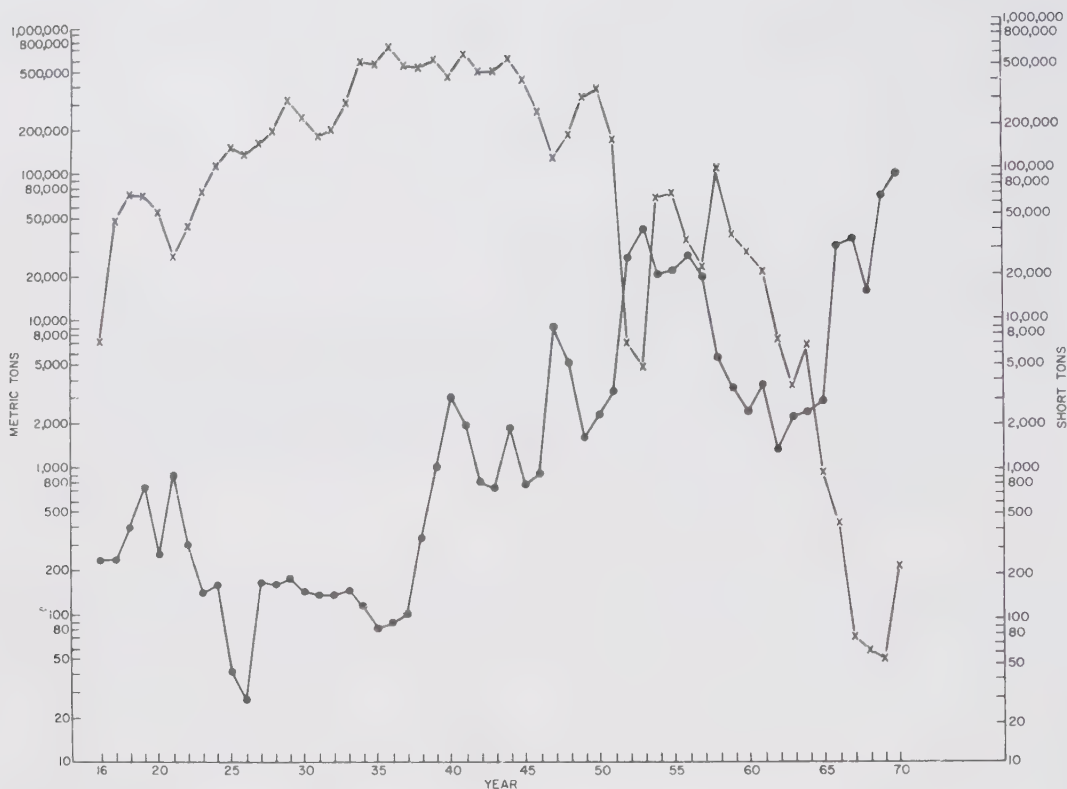


FIGURE 1.—The annual catch of sardine (crosses) and anchovy (solid circles) in the California Current system since 1916. Whole fish reduction was essentially banned in 1919 and a limited whole fish reduction fishery was opened in 1965.

1964)² in an informal statement, emphasized the changing ratio of anchovy larvae to sardine larvae from 3.1 to 1 in 1951 to 46.8 to 1 in 1959. In a similarly informal statement, MacGregor (MRC, 1964) described a method for estimating the spawning biomass of pelagic spawning species. That portion of his statement which is related to sardine and anchovy follows:

Egg and larval surveys conducted over the years have given us a basis for estimating the total numbers of eggs and larvae produced each year in the CalCOFI

(California Cooperative Oceanic Fisheries Investigations) survey area for a number of fish species. We also have information on the fecundity of a number of these species and from the combined data can estimate the biomass of spawning adult fish on each species. The number of eggs a fish will produce at one spawning appears to be directly related to the weight of the fish. Thus, we can compute the numbers of eggs produced in one spawning by a ton of female fish as follows:

Species	Millions of eggs
Anchovy	525
.....	..
Sardine	241
.....	..

The above figures represent female fish only. If we assume, as evidence indicates, that for each ton of adult females there is also present a ton of adult males, we would have to divide the number of eggs produced

² A review of estimates and procedures was conducted for the California Marine Research Committee (MRC) in 1964 and the texts of the presentations are to be found there. Statements and calculations were neither edited nor formally derived. Quotations from the Appendix to these minutes will be regarded as informal and cited (MRC, date).

by 2 to obtain the number of eggs produced [in one spawning]^a by one ton of adult fish. If we further assume that . . . about half the [adult] sardine population spawns twice [a year] (average 1½ times) and the anchovy [adult] population spawns 2 or 3 times a year (average 2½ times), we would also multiply millions of eggs by 1½ for the sardine and 2½ for the anchovy. On the above basis the total number of eggs produced by one ton of adult fish of both sexes in one year would be as follows for each species:

Species	Millions of eggs
Anchovy	656
.....	..
Sardine	181
.....	..

It may be seen from the above that, although numbers of eggs or larvae in the plankton may be used as an index of adult abundance, a sardine egg in the plankton represents 3½ times . . . as much adult biomass as an anchovy egg. Estimates of the average biomass of each . . . species for the 3-year period 1955-57 and the average commercial landings for the same period are as follows:

	Biomass	Catch
Species	(tons)	(tons)
Anchovy*	750,000	29,686
.....		
Sardine	254,000	51,508

* Anchovy larvae caught were used as an estimate of eggs. This may have resulted in underestimation by a factor of 2. Application of this factor brings this biomass of anchovies into line with the material in Murphy's (MRC, 1964) estimate of the anchovy harvest

^a In brackets added for clarification.

In another informal statement Radovich (MRC, 1965) cited the change in anchovy to sardine larval ratios (Ahlstrom, MRC, 1964) and stated ". . . in this 8-year period the anchovy maintained its population level fifteen times better than the sardine . . ." He further pointed out that the necessary ratio of annual survival rates to attain this was 1.4. Should this difference in survival be in the larval stage, the MacGregor (MRC, 1964) biomass estimate should be divided by 1.4 or roughly 1.5, resulting in an estimate of about 1 million tons.

Murphy (MRC, 1964) used an anchovy spawner biomass estimate which was essentially double MacGregor's (MRC, 1964) because he believed that the escapement of anchovy larvae through the mesh of the standard CalCOFI silk net exceeded the escapement of the sardine larvae enough to cancel the effect of anchovy fecundity exceeding sardine fecundity. Thus Murphy's calculation (1966, p. 60) of anchovy spawner biomass for the period 1955-57 was 3.3 million short tons as compared to MacGregor's 1.5 million short tons and Radovich's 1.0 million short tons for the same 3-year period. An estimate by Murphy's method for 1958 would be 5.1 million short tons.

Ahlstrom (1968) estimated that the 1958 anchovy biomass was between 1.80 and 2.25 million short tons and observed further that the biomass had reached a plateau of 4.5 to 5.625 million short tons in the mid-1960's.

TABLE 1.—Comparison of data used for estimating the spawning biomass of northern anchovy.

	Standard haul summation ¹		Summation of average quarterly estimates ²		Larval census estimates ³		Standard haul summations ⁴	
	Anchovy	Sardine	Anchovy	Sardine	Anchovy	Sardine	Anchovy	Sardine
1951	29,551	11,068	9,826	3,689	15,101	5,774	29,552	11,066
1952	59,626	19,179	20,581	6,437	17,071	5,466	63,057	24,559
1953	99,160	14,400	34,314	4,924	23,680	4,020	103,928	15,055
1954	161,241	26,914	56,665	9,364	38,415	7,297	161,254	26,914
1955	140,183	14,121	51,096	5,554	37,658	4,341	140,183	14,121
1956	134,931	15,523	51,438	5,179	38,508	3,895	134,931	15,523
1957	146,631	9,833	53,921	3,415	40,441	2,432	146,631	9,833
1958	205,733	11,427	75,120	3,845	56,928	2,831	205,457	11,423
1959	206,753	5,374	72,732	2,072	54,168	1,159	206,000	5,308
1960	289,860	8,012	97,602	3,099				
1961	97,103*	1,708*	97,103	1,708				
1962	212,675*	2,258*	212,675	2,258				
1963	205,838*	1,349*	205,838	1,349				
1964	166,517*	2,757*	166,517	2,757				
1965	258,781*	3,573*	258,781	3,603				
1966	380,420	5,640	161,333	2,211				

¹ Ahlstrom 1966, tables 2 and 4 (1965, 1966, numbers from current unpublished data).

² Ahlstrom, 1966, 1968.

³ Ahlstrom, 1968.

⁴ Murphy, 1966.

* Quarterly cruises rather than monthly.

TABLE 2.—Stations and pooled areas within each region as used in this study.

Regional name	Pooled areas	Stations	Regional name	Pooled areas	Stations
Central California Inshore	6.5	60.52			87.80
18 stations	5,270 miles ²	60.55		8.9	80.90
4 pooled areas		63.52			83.90
19,970 miles ²		63.55		9.7	87.90
		67.50			90.70
		67.55			93.70
	6.6	60.60			97.70
4,800 miles ²		63.60		9.8	90.80
		67.60			93.80
	7.5	70.52 (51)			97.80
5,100 miles ²		70.55 (53)		9.9	90.90
		73.51 (50)			93.90
		73.55 (53)			97.90
		77.50 (51)	Baja California inshore	10.3	100.29
	7.6	70.60	29 stations	5,535 miles ²	100.30
4,800 miles ²		73.60	4 pooled areas		100.35
		77.60	21,089 miles ²		103.30
					103.35
Central California offshore	6.7	60.70			107.32
6 stations	6.8	60.80			107.35
6 pooled areas	6.9	60.90		10.4	100.40
28,800 miles ²		70.70	4,800 miles ²		103.40
	7.7	70.70			103.45
	7.8	70.80			107.40
	7.9	70.90		11.3	110.33 (32)
Southern California inshore	8.4	82.47		5,956 miles ²	110.35
19 stations	4,589 miles ²	83.40			113.30
3 pooled areas		83.43			113.35
15,348 miles ²		87.35			117.26
		87.40			117.30
		87.45			117.35
	9.3	90.28			118.39
	5,989 miles ²	90.30 (32)			119.33
		90.37			120.25
		93.27 (28)			120.30
		93.30			120.35
		97.30		11.4	110.40
		97.32	4,798 miles ²		110.45
		97.35			113.40
	9.4	90.45			113.45
4,770 miles ²		93.40			117.40
		93.45			117.45
		97.40			
		97.45	Baja California offshore	10.5	100.50
Southern California offshore	8.5	80.51 (52)	15 stations	4,800 miles ²	103.50
18 stations	4,747 miles ²	80.55	4 pooled areas		107.50
4 pooled areas		83.51	19,200 miles ²	10.6	100.60
19,147 miles ²		83.55	4,800 miles ²		103.60
		87.50			107.60
		87.55		11.5	110.50
	8.6	80.60	4,800 miles ²		110.55
4,800 miles ²		83.60			113.50
		87.60			113.55
	9.5	90.50			117.50
4,800 miles ²		90.55 (53)			117.55
		93.50		11.6	110.60
		93.55	4,800 miles ²		113.60
		97.50			117.60
		97.55	Baja California seaward	10.7	100.70
	9.6	90.60	19 stations	4,800 miles ²	103.70
4,800 miles ²		93.60	6 pooled areas		107.70
		97.60	28,800 miles ²	10.8	100.80
Southern California seaward	8.7	80.70	4,800 miles ²		103.80
18 stations		83.70			107.80
6 pooled areas		87.70		10.9	100.90
28,800 miles ²	8.8	80.80	4,800 miles ²		103.90
		83.80			107.90
				11.7	110.70

TABLE 2.—Continued.

Regional name	Pooled areas	Stations	Regional name	Pooled areas	Stations
	4,800 miles ²	113.70		4,800 miles ²	130.45
		117.70			133.40
		117.75			133.45
	11.8	110.80			137.40
	4,800 miles ²	113.80			137.45
		117.80			
	11.9	110.90	South Baja offshore	12.5	120.50
	4,800 miles ²	113.90	16 stations	4,800 miles ²	120.55
		117.90	4 pooled areas		123.50
			19,200 miles ²		123.55
South Baja inshore	12.3	123.37			127.50
22 stations	4,459 miles ²	127.34			127.55
5 pooled areas	12.4	120.40		12.6	120.60
22,790 miles ²	4,800 miles ²	120.45	4,800 miles ²		123.60
		123.42			127.60
		123.45		13.5	130.50
		127.40	4,800 miles ²		130.55
		127.45			133.50
	13.2	133.25			137.50
	3,931 miles ²	137.23		13.6	130.60
	13.3	130.30	4,800 miles ²		133.60
	4,800 miles ²	130.35			137.60
		133.30			
		133.35	South Baja seaward	12.7	120.70
		137.30	3 stations	12.8	120.80
		137.35	3 pooled areas	12.9	120.90
	13.4	130.40	14,400 miles ²		

Murphy (1966) estimated the biomass of the spawning stocks of sardine from 1932 to 1959. He also compared the anchovy:sardine larval ratio from 1951 to 1959 and graphically compared this with the larval ratio over a portion (about 20%) of their joint range in 1940 and 1941 (p. 65). The striking decline of the sardine, and the increase of the anchovy biomass, has stimulated speculation on the biological interactions of these species and the MRC (Marine Research Committee of California) has a standing recommendation that 200,000 tons of anchovies and 10,000 tons of sardines be harvested in an experimental attempt to foster the recovery of sardines. It is the primary goal of this recommendation to restore and maintain the balance of sardines and anchovies in the California Current system by manipulation of fishing effort.

The estimates of spawning biomass of the northern anchovy have been based on the spawning biomass of the Pacific sardine as derived from the fishery (Murphy, 1966; Ahlstrom, 1968) and on the assumed relationship between sardine and anchovy fecundity, survival, and escapement of larvae through the meshes of the CalCOFI standard silk survey net (Lenarz, 1972). For convenience, the larva data for all

estimates to date are listed in Table 1. A series of stations off southern California was occupied in 1940 and 1941, and the anchovy:sardine ratios were 1.18 (13,962 anchovy to 11,862 sardines) and 1.66 (12,560 anchovy to 7,564 sardines) respectively. The 1940, 1941, 1949, and 1950 data will be referred to later in a section on interaction of sardine and anchovy.

METHOD OF DATA ASSEMBLY

The method of assembling the estimates of larval abundance for this paper differs from that of Sette and Ahlstrom (1948) and Ahlstrom (1954, 1966, 1967, 1968). Two methods of assembly were used previously: the "census estimate" and the "standard haul summation." In the "census estimate" each larva sample count was weighted by the area of a polygon formed by construction of "perpendicular bisectors of lines drawn from the station to each of all surrounding stations" (Sette and Ahlstrom, 1948, p. 521; Ahlstrom, 1968).

$$C_k = 10 \sum_{j=1}^n \left[\sum_{i=1}^m A_i \left(a_i^{-2} b_i^{-1} c_i d_i \right) \right]_j \quad (1)$$

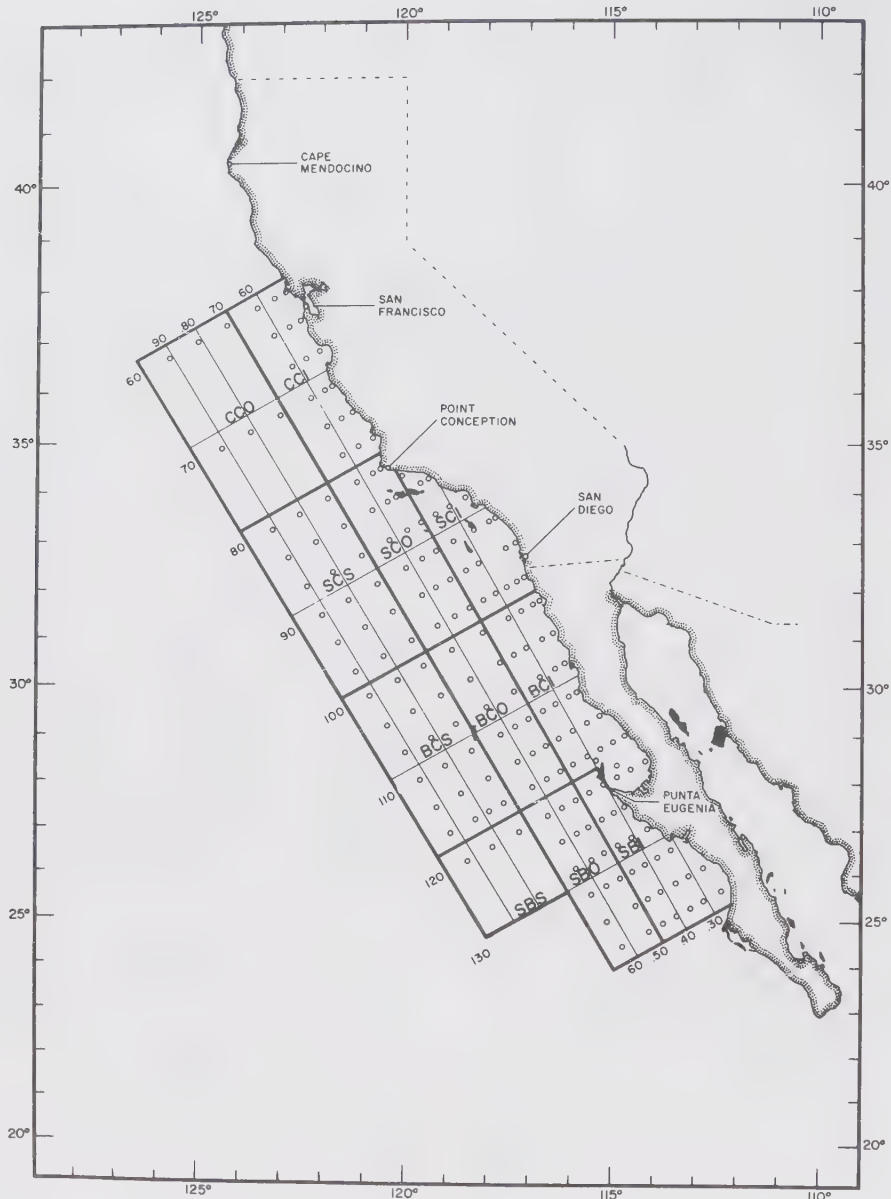


FIGURE 2.—The selected stations of the CalCOFI grid (see Tables 2 and 3) and the regional boundaries defined for this paper. Columns of stations are indicated .30, .40 90, and rows of lines are indicated 60, 70, . . . 130. The first two letters of each three-letter group stand for coastal bands, i.e., central California (CC), Southern California (SC), Baja California (BC), South Baja (SB) while the last letter of the three stands for offshore zones roughly parallel to the coast, inshore (0-80 miles from the coast, "I", offshore (80-160 miles from the coast, "O"), and seaward (160-280 miles from the coast, "S"), so that the three letters SCI stand for the southern California inshore region.

TABLE 3.—Description of CalCOFI regions used in this analysis.

Regional name	Stations	Pooled areas	Square miles	Area factor
Central California inshore	18	4	19,970	6.85×10^9
Central California offshore	6	6	28,800	9.88
Southern California inshore	19	3	15,348	5.26
Southern California offshore	18	4	19,147	6.57
Southern California seaward	18	6	28,800	9.88
Baja California inshore	29	4	21,089	7.23
Baja California offshore	15	4	19,200	6.58
Baja California seaward	19	6	28,800	9.88
South Baja inshore	22	5	22,790	7.82
South Baja offshore	16	4	19,200	6.58
South Baja seaward	3	3	14,400	4.94
Totals	183	49	237,544	81.48

TABLE 4.—Equivalent station list off southern California for 1940, 1941, and 1950-72.

Southern California inshore			Southern California offshore		
Station no. used in 1940	Station no. used in 1941	Nearest present station no.	Station no. used in 1940	Station no. used in 1941	Nearest present station no.
02	12	82.47	04	15	80.51
01	11	83.40	05	16	80.55
08	23	83.43	03	13	83.51
10	21	87.35	13	14	83.55
17	22	87.40	24	24	87.50
11	34	87.45	12	25	87.55
21	30	90.28	06	28	80.60
19	31	90.30	09	27	83.60
20	32	90.37	18	26	87.60
22	41	93.27	23	35	90.50
28	51	90.30	31	36	90.55
--	60	97.30	39	45	93.50
35	61	97.32	40	46	93.55
36	62	97.35	41	64	97.50
30	33	90.45	14	55	97.55
29	52	93.40	32	37	90.60
34	54	93.45	25	47	93.60
37	63	97.40	33	--	97.60
38	53	97.45			

where A_s = area of a polygon constructed of perpendicular bisectors of lines between station "i" and all adjacent stations expressed as number of 10 m² areas

C_{kf} = estimate of abundance of larvae in year "k" and "f" takes the value of the number of the equation

C_i = number of larvae in "ith" sample

a_i = area of mouth of the net used at the "ith" station

b_i = length of tow in meters estimated from a calibrated flow meter at station "i"

d_i = tow depth in meters estimated

from the wire angle at maximum wire out at station "i"

m = number of stations

n = number of monthly cruises.

In the "standard haul summation" approach the sums of all tows on regularly occupied stations for each monthly cruise were totaled for the year without weighting for represented area.

$$C_k = 10 \sum_{j=1}^n \left[\sum_{i=1}^m (a_i^{-2} b_i^{-1} c_i d_i) \right]_j \quad (2)$$

To accommodate the quarterly cruises Ahlstrom (1966, 1968) established a modification of this in which the quarterly averages of 1 to 3 monthly cruise summations were added to make an

annual total (Ahlstrom, 1966, Table 8; 1968, Table 3).

$$C_k = 10 \sum_{q=1}^4 \left\{ \sum_{j=1}^n \left[\sum_{i=1}^m \left(a_i^{-2} b_i^{-1} c_i d_i \right) \right]_j n^{-1} \right\}_q \quad (3)$$

Murphy (1966) used the monthly version of Ahlstrom's standard haul summation (Table 1).

The method used here is called the "regional census estimate"

$$C_{k4} = 10 A_r m^{-1} \left[\sum_{i=1}^m \left(a_i^{-2} b_i^{-1} c_i d_i \right) \right] \quad (4)$$

where C_{k4} = estimate of abundance of larvae in region "r" in each quarter

A_r = Area of region "r" in numbers of 10 m² areas.

This method of assembly combines the simplicity of the "standard haul summation" and the areal weighting of the previously used census estimates. The regional census estimate consists of the mean number of larvae per standard area (10 m² sea surface) of all stations taken within a region for a quarter of the year times the number of standard areas within the region. The same 183 stations or nearby alternates were used within the routinely occupied area as defined by Smith, Ahlstrom, and Casey (1970, Figure 1). The selected stations and acceptable alternates are listed in Table 2 and the regions are illustrated in Figure 2 and defined by area and area factor in Table 3.

The 1940 and 1941 stations have been assigned to the two southern California regions (Table 4) in which these cruises were conducted. The number of stations per unit area has been held nearly constant by the elimination of excess stations in the early cruises. The 1949 station equivalents are listed in Table 5. From 1950 to 1972 stations have been standard in placement.

TABLE 5.—Equivalent station list for the CalCOFI survey pattern for 1949 and 1950-72.

Area	Station no. used in 1949	Nearest present station no.
Central California inshore	601 701	63.68 72.56
Central California offshore	602 603 604 702 703 704	62.68 61.78 61.87 71.66 71.76 71.85
Southern California inshore	901	92.39
Southern California offshore	801 902 903	82.57 92.48 92.58
Southern California seaward	802 803 804 904 905	82.67 82.77 82.87 92.68 92.78
Baja California inshore	1001 1002 1101 1102	101.34 101.44 111.38 111.48
Baja California offshore	1003 1004 1103	102.54 102.64 111.58
Baja California seaward	1005 1006 1007 1104 1105 1106 1107	102.74 102.84 102.94 111.68 112.78 112.88 112.98
Southern Baja inshore	1201	122.44
Southern Baja Offshore	1202	122.53
Southern Baja seaward	1203 1204 1205	123.63 123.73 124.83

Extra cruises, additional lines, and stations on lines have been added periodically, resulting in some increase in station density in some areas. To stabilize sampling effort and remove possible effects of added effort nearshore, all but 183 stations and their nearby equivalents have been eliminated from further consideration for the 16-year compilation of regional census estimates. The number of stations eliminated each year are summarized in Table 6.

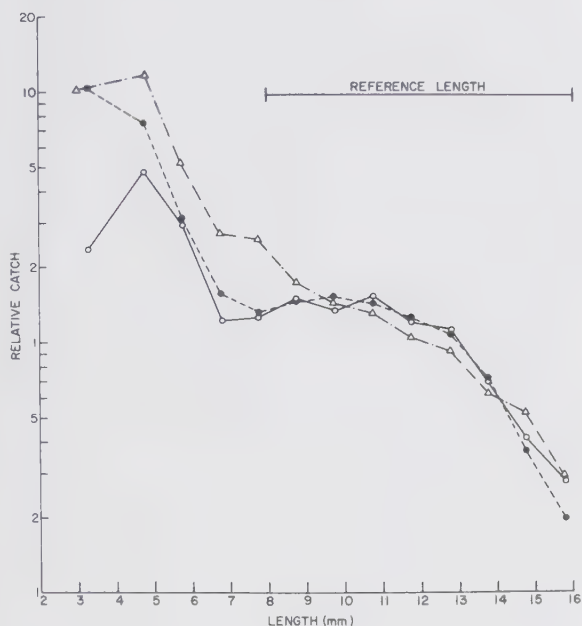


FIGURE 3.—The size frequency of sardine larvae caught in the CalCOFI standard silk net (0.55 mm). The triangle dot-dash curve represents the 1951-60 catch from the selected stations in all eleven regions; the black dot-dash curve represents the 1940 catch from selected stations in the southern California inshore and offshore region and the clear dot solid line represents the 1941 catch from the same two regions. Relative catch refers to the catch at a standard size group (3.00, 3.25 (1940-41), 4.75, 5.75 ... 15.75 mm), divided by the average catch from size groups 8.75 to 15.75.

ESCAPEMENT AND AVOIDANCE BY ANCHOVY AND SARDINE LARVAE

The chief errors causing underestimates of C for both anchovy and sardine larvae are those attributable to larvae "escaping" through the meshes of the standard plankton net (see Lenarz, 1972, p. 839) and larvae "avoiding" the mouth of the net (Silliman, 1948; Ahlstrom, 1954, 1959; Clutter and Anraku, 1968). While "escapement" and "avoidance" are important biases to consider in the study of larva growth and mortality, I consider them beyond the scope of this paper. The estimate of anchovy biomass is based on a relative estimate of the number of anchovy larvae and sardine larvae. I must treat escapement and avoidance briefly, since they act differently on the anchovy and sardine and vary from season to season and with changes in sampling gear.

Lenarz (1972) found no appreciable difference in size-specific escapement of sardine and anchovy through net apertures. However, newly hatched anchovy larvae are considerably smaller than sardine larvae. This leads to a variation in the degree of bias (Murphy, 1966) to such escapement. In Figure 3 the catch of all standard sizes of sardine is related to the average catch between 8.75 and 15.75 mm, a size range I assume to be completely retained on 0.55-mm mesh width silk. The primary line is the average size composition for the period 1951-60 for the sardine. The size composition of the 1940

TABLE 6.—Stations eliminated from data assembly for regional census estimates.

Year	No. of stations occupied	183 stations reported each cruise	Stations not reported	Percent reported
1951	1,436	1,026	410	71.4
1952	1,376	1,167	209	84.8
1953	1,346	1,137	209	84.5
1954	1,473	1,217	256	82.6
1955	1,425	1,121	304	78.7
1956	1,399	1,129	270	80.7
1957	1,493	1,165	328	78.0
1958	1,851	1,276	575	68.9
1959	2,182	1,574	608	72.1
1960	1,810	1,305	505	72.1
1961	953	699	254	73.3
1962	920	659	261	71.6
1963	881	659	222	74.8
1964	877	680	197	77.5
1965	1,099	658	441	59.9
1966	1,979	1,487	492	75.1

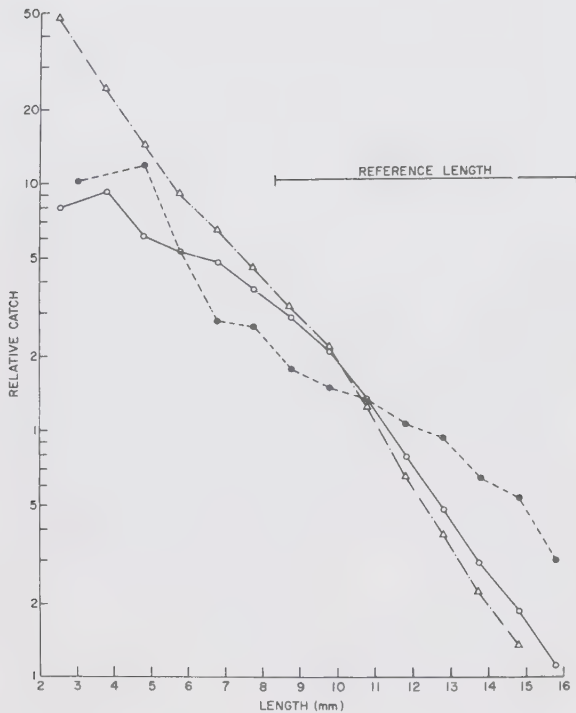


FIGURE 4.—The size frequency of sardine and anchovy larvae. The black dot-dash line is sardine larvae caught in the standard CalCOFI silk net between 1951 and 1960 in all regions from January to June inclusive. The clear dot solid line is anchovy larvae caught in the standard CalCOFI silk net between 1951 and 1960, in all regions from January to June inclusive. The triangle dot-dash line is anchovy larvae caught in the new CalCOFI nylon net (0.505-mm nylon rather than 0.55-mm silk) from January to June 1969 in all regions.

and 1941 sardine catches are included for later reference. In Figure 4, the 1951-60 size composition of sardine is compared to the anchovy for the same period. Anchovy retention in a new net with smaller, more regular meshes (0.505-mm nylon) and more mesh area is included for comparison. All samples reported in the size frequency graphs are from the first half of the year to facilitate comparison with earlier samples and eliminate the effects of poor sampling coverage in the latter half of the year.

Ahlstrom (1954) acknowledged that larger larvae may avoid capture at night as in the daytime. Avoidance is more pronounced in

the daylight. In the sardine the night-to-day ratio of catches increases 0.6971 per mm of growth after 4.75 mm (Ahlstrom, 1954, p. 129). Similarly, the anchovy night-to-day catch ratio increases 0.64 for each millimeter growth after 3.5 mm (Ahlstrom, 1959, p. 136). Lenarz (in press) described the annual and diurnal variation in size specific catch rate for sardine, anchovy, hake, and jack mackerel. An important source of variability in avoidance bias is a shift of spawning season. For example, length of day varies from 9.6 hr in winter to 14.8 hr in summer at the latitude of San Francisco near the northern boundary of the survey grid and from 10.6 to 13.7 hr off south Baja California at the southern boundary of the sample grid (54% and 29% respectively). For the 10-year period, 1951-60, the ratio of night-caught to day-caught larvae was 1.72 for sardines and 2.45:1 for anchovy. When the average catch per positive tow by month is corrected for day length at San Francisco the anchovy:sardine ratio changes from 2.96:1 to 3.75:1 for the same decade. A proportionate shift of anchovy spawning toward June would for example, accentuate this difference.

The importance of avoidance and escapement

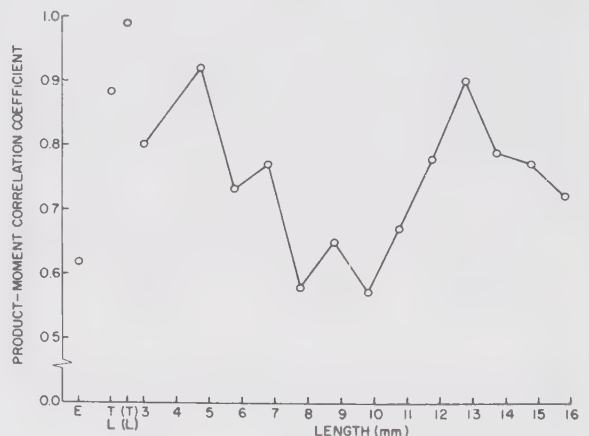


FIGURE 5.—The correlation coefficient between the annual total regional census estimates of sardine eggs and larvae by size class with the Murphy (1966) sardine biomass estimates. The first point is for total eggs, 1951-59; the second point is for total larvae, 1951-59; the third point is for total larvae with 1953 and 1959 censored. The succeeding points are for standard-size classes for all years 1951-59.

TABLE 7.—A comparison of the regional census estimate (A), separately weighted nearshore (B), and 1 month per quarter sampling (C), in the southern California inshore region, 1951-60.

		Winter	Spring	Summer	Fall	Total	Annual rank
1951	A	135	609	111	540	1,395	9
	B	175	879	92	441	1,587	9
	C	289	251	76	276	892	10
1952	A	87	261	314	134	796	10
	B	70	229	336	119	754	10
	C	52	315	531	122	1,020	9
1953	A	578	184	763	1,904	3,429	6
	B	519	139	734	1,409	2,801	6
	C	163	339	1,089	728	2,319	8
1954	A	3,123	516	519	237	4,395	3
	B	1,006	445	412	180	2,043	7
	C	2,577	332	934	149	3,992	5
1955	A	2,012	1,074	849	150	4,085	4
	B	1,682	1,006	737	117	3,542	4
	C	1,941	930	1,111	55	4,037	4
1956	A	236	1,166	708	156	2,266	8
	B	186	1,009	635	117	1,947	8
	C	302	1,632	708	129	2,771	7
1957	A	3,314	3,601	791	267	7,973	1
	B	3,650	3,264	933	238	8,085	1
	C	4,951*	4,060	791	154	9,956	1
1958	A	2,316	2,912	403	63	5,694	2
	B	2,186	3,226	417	36	5,865	2
	C	1,753	4,246	554	51	6,604	2
1959	A	972	2,303	108	101	3,484	5
	B	907	2,590	111	72	3,640	3
	C	413	5,354	218	19	6,004	3
1960	A	1,579	1,448	198	34	3,259	7
	B	1,692	1,564	189	36	3,481	5
	C	263	2,394	296	34	2,987	6

* February

B $r_s = 0.85$ C $r_s = 0.90$

to biomass estimation is solely a function of the variability these biases cause with respect to year-to-year differences between the capture and retention of sardine and anchovy larvae. For example, in Figure 5 the product moment regression coefficients, r for sardine egg or larval census estimate versus sardine biomass are plotted by total eggs, total larvae (1951-59), total larvae with outlier censored (1953-59), and each larval size interval through 15.75 mm. All the coefficients are high and positive with pronounced minima at the egg stage and at the 9.75 mm stage. One might ascribe the minimum associated with eggs to the effect of "patchy" distribution on precision of estimate. I have no ready explanation of the 9.75 mm minimum or the 12.75 mm maximum which follows it.

Sette and Ahlstrom (1948, p. 521) discussed the concept of "area of station" relative to sardine eggs. Trial calculations of the same kind suggest that with respect to sardine larvae, assigning equal areas to stations is also close to the more exact method of erecting perpendicular bisectors to each nearest station and using the area of the polygon so formed. For anchovy larvae, however, there may be an important problem. To study this problem, the southern California inshore region was divided into "nearshore", i.e., the standard station closest to shore on each line, and "nearshore-excluded" segments. In the 40 quarters of the years 1951-60, the mean concentration of eggs per positive station in the "nearshore" region exceeded that of the "nearshore-excluded" section by 35%. Similarly the

proportion of positive stations was 87% "near-shore" and 68% in the "nearshore-excluded" region with respect to anchovy larvae.

In Table 7 I have compared the annual estimates of anchovy larvae using the quarterly regional census estimate of the entire region with the same estimate using the sum of the near-shore and nearshore-excluded segments of the region. The latter estimate is 8% lower than the regional census estimate, but it is not likely to be a bias since of the 10 annual estimates, the single estimate exceeds the partitioned estimate 5 times while the reverse is true an equal number of times. The Spearman rank coefficient of correlation is 0.85. Also, a comparison of the annual estimates from 1951 to 1959 regional census estimates and those from a census estimate by Ahlstrom (1967, Table 2) shows a Spearman rank correlation coefficient of 1.00. Thus, we may conclude that errors of the kind involving nearshore gradients in the incidence and intensity of anchovy spawning and larval survival, while important for some applications, do not measurably affect the regional census estimates.

One may reasonably ask whether estimates generated from monthly cruises are comparable to larval abundance estimates from a single cruise in each quarter. In Table 7 I have compared the annual estimates of anchovy larvae using all regular occupied stations within the quarter and a similar estimate using only January, April, July, and October, with February used in 1957 because the January cruise was incomplete. The Spearman rank coefficient for the comparison is 0.90: the mean value of the estimates from monthly cruises is 10% below the estimates from one cruise per quarter but in 5 years the monthly derived estimates exceed the quarterly and in 5 years the reverse is true. Thus, I conclude that differences which may arise from comparing estimates from quarterly and monthly cruises are not large enough to affect this study.

Technical errors should be relatively small and affect the catches of sardine and anchovy similarly. For example, the factor a , the area of mouth of the net is usually known to within 5%, the factor b , is modified by the flow through the mouth of the net so that the length of tow is

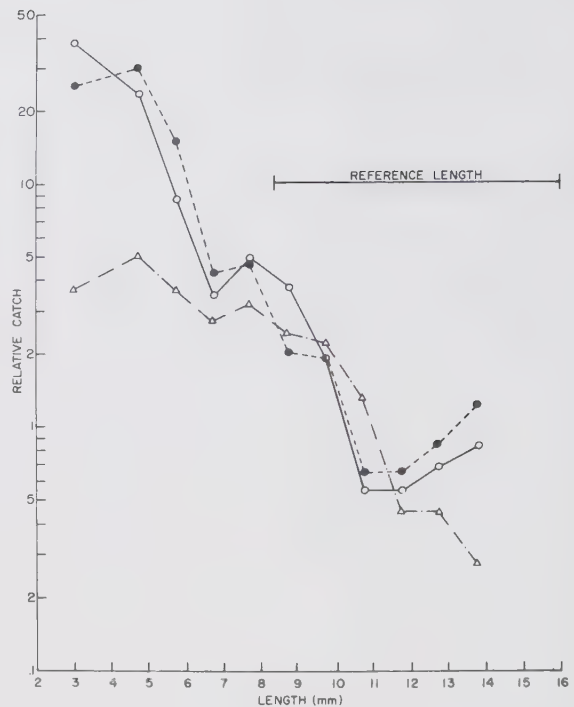


FIGURE 6.—The size frequency of sardine larvae captured in 1951-60 in the southern California inshore (clear dot, solid line), offshore (black dot, small dash), and seaward (triangle, large dash) regions. The size frequency effect is attributed to offshore transport (see text).

underestimated by 13-15%: an error as great as 5-10% results from the flowmeter being centered in the backwash of the bridle apex hardware (Smith and Clutter, 1965; Tranter and Smith, 1968; Mahnken and Jossi, 1967).

Two biases, which have yet to be evaluated, are likely to be important. In cold water, the larvae may tend to grow more slowly. Thus the regional census estimate for a cold quarter or cold year could prolong the period for which the larvae are vulnerable to sampling. Similarly, larvae may persist without food for extended periods yielding the same kind of error mentioned for temperature. No estimate has been made for either bias for anchovy or sardine larvae.

All the sardine and anchovy larvae collected by the CalCOFI net have been subjected to trans-

port with the wind-driven layer of the ocean (Sette, 1943). While the entire problem of transport is beyond the scope of this paper, a comparison of size frequencies of larvae in the southern California inshore, offshore, and seaward regions shows a disproportionately lower number of younger larvae in samples from farther offshore (Figures 6 and 7). The most likely explanation of these data is that older larvae transported to the offshore regions are present in excess of the numbers that have been spawned and hatched there. Further, this implies that the larva size frequency slope in the spawning area is biased for the same reason. If the usual sampling grid encloses the spawning area and the areas to which larvae are transported no overall bias should ensue.

The MacGregor estimate of anchovy and sardine biomass cited above, mentioned specific numbers of spawnings per year and sex ratios. Neither of these has been suitably evaluated as yet. At present, there is no way of calculating the number of batches spawned per year. In this paper, I assume that the anchovy is twice as fecund as sardine. An attempt will be made to evaluate the sensitivity to multiple spawning by proposing three spawning models, below. The sex ratio is presently derived from the fishery which is conducted over a very small proportion of the anchovy range. Since males are somewhat smaller, they may be expected to be recruited to

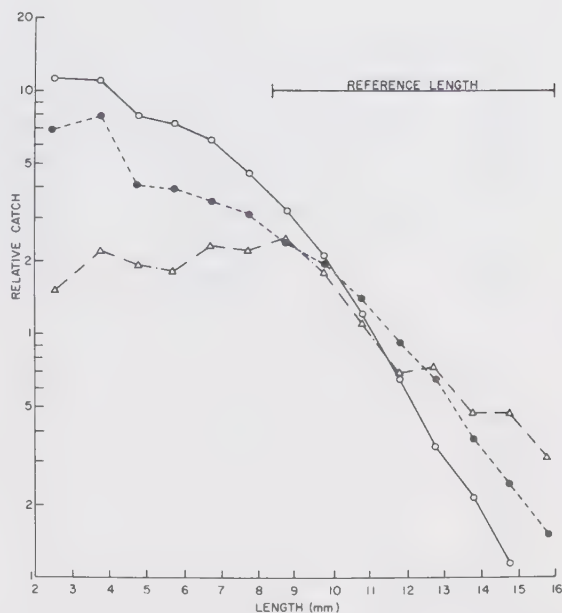


FIGURE 7.—The size frequency of anchovy larvae captured in 1951-60 in the southern California inshore (clear dot, solid line), offshore (black dot, small dash), and seaward (triangle, large dash) regions. The size frequency effect is attributed to offshore transport (see text).

the fishery somewhat later than females. In this report, the simple assumption of equality of biomass will be maintained. This will tend to overestimate the adult biomass by the degree in which the male biomass is overestimated.

TABLE 8.—Sample size frequency distribution for sardine and anchovy. Total larvae per 10 m² sea surface.

Mid-range <i>x</i>	Sardine <i>f</i>	<i>f</i> / <i>x</i>	<i>f</i> / <i>Σf</i> / <i>x</i>	Cumulative percent	Anchovy <i>f</i>	<i>f</i> / <i>x</i>	<i>f</i> / <i>Σf</i> / <i>x</i>	Cumulative percent
0.7	4	2.8	0.000	0.0	4	2.8	0.000	0.0
1.4	51	71.4	0.000	0.1	79	110.6	0.000	0.0
2.8	453	1,268.4	0.009	0.9	886	2,480.8	0.002	0.2
5.6	320	1,792.0	0.012	2.2	707	3,959.2	0.003	0.4
11.2	312	3,494.4	0.024	4.6	814	9,116.8	0.006	1.0
22.4	289	6,473.6	0.045	9.1	789	17,673.6	0.012	2.2
44.7	257	11,487.9	0.079	17.0	752	33,614.4	0.022	4.4
89.1	179	15,948.9	0.110	28.0	725	64,597.5	0.043	8.7
177.8	127	22,580.6	0.156	43.7	618	109,880.4	0.072	15.9
354.8	78	27,674.4	0.191	62.8	579	205,429.2	0.135	29.4
707.9	44	31,147.6	0.216	84.4	369	261,215.1	0.172	46.6
1,412.5	14	19,775.0	0.137	98.0	247	348,887.5	0.230	69.6
2,818.4	1	2,818.4	0.019	100.0	94	264,929.6	0.174	87.1
5,623.4					23	129,338.2	0.085	95.6
11,220.2					4	44,880.8	0.030	98.5
22,387.2					1	22,387.2	0.015	100.0
<i>N</i>	2,129				6,691			
$\bar{X}$	67.88				226.95			
$\Sigma f/x$		144,535.4				1,518,503.7		

TABLE 9.—Regional census estimates of total anchovy larvae (0-: no sampling).

Year	Quar- ter	Regions ¹											Total
		CCI	OCO	SCI	SCO	SCS	BCI	BCO	BCS	SBI	SBO	SBS	
1940	1	0—	0—	771	196	0—	0—	0—	0—	0—	0—	0—	967
	2	0—	0—	258	214	0—	0—	0—	0—	0—	0—	0—	472
	3	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
	4	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
1941	1	0—	0—	184	351	0—	0—	0—	0—	0—	0—	0—	535
	2	0—	0—	422	579	0—	0—	0—	0—	0—	0—	0—	1,001
	3	0—	0—	27	8	0—	0—	0—	0—	0—	0—	0—	35
	4	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
1950	1	0	0	10	9	4	43	17	1	13	5	0	102
	2	0	0	232	319	27	115	23	0	152	13	0	881
	3	994	265	338	5	2	9	1	0	2	3	0	1,619
	4	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
1951	1	5	0	135	8	0	289	17	150	2,537	147	1	3,289
	2	4	6	609	24	5	203	66	78	289	179	80	1,543
	3	25	53	111	21	0	454	0	0	49	57	0	770
	4	18	0	540	21	0	266	2	0	55	0	0	902
1952	1	0—	0—	87	33	0	1,372	111	0	1,762	40	0	3,405
	2	0	0	261	7	1	732	32	0	1,665	145	0	2,843
	3	7	69	314	16	3	462	1	2	240	12	2	1,128
	4	0	0	134	23	0	558	31	0	8	2	0	756
1953	1	0—	0—	578	67	6	1,649	247	2	4,160	78	227	7,014
	2	0	0	184	17	0	535	85	2	424	238	14	1,499
	3	2	0	763	36	7	373	2	0	150	33	0	1,368
	4	0—	0—	1,904	882	0	831	48	0	84	2	0	3,751
1954	1	654	0—	3,123	723	6	1,090	97	6	4,116	474	615	10,904
	2	1	0	516	98	2	878	28	3	1,872	498	390	4,246
	3	451	0	519	307	426	182	0	0	231	191	0	2,307
	4	58	0—	237	73	11	234	153	0	301	9	0	1,076
1955	1	0—	0—	2,012	283	6	7,152	499	11	750	312	2	11,027
	2	2	0	1,074	246	6	540	266	296	787	380	24	3,621
	3	7	0	849	184	35	257	3	0	602	9	27	1,973
	4	5	10	150	19	0	210	15	0	59	7	4	479
1956	1	0—	0—	236	203	46	1,140	832	409	1,786	1,107	2	5,761
	2	0	0	1,166	63	14	2,239	37	1	1,737	154	2	5,413
	3	247	0	708	562	21	1,413	0	0	807	8	0	3,766
	4	0—	0—	156	115	4	0—	0—	0—	0—	0—	0—	275
1957	1	0—	0—	3,314	1,085	969	2,720	102	3	2,683	69	0	10,945
	2	20	21	3,601	814	69	853	104	8	426	44	13	5,973
	3	5	20	791	592	64	380	1	0	358	234	17	2,462
	4	64	0	267	229	4	86	0	0	10	0	0	660
1958	1	1,620	1,227	2,316	2,407	268	4,680	618	16	4,606	788	5	18,551
	2	252	15	2,912	1,163	497	1,099	384	2	165	57	44	6,590
	3	413	387	403	1,508	84	143	5	0	15	0	0	2,958
	4	11	5	63	34	0	54	2	0	4	0	0	173
1959	1	1,722	0	972	4,452	654	701	51	1	1,595	51	0	10,199
	2	1,101	318	2,303	3,074	498	3,227	651	1	464	453	0	12,090
	3	232	128	108	242	33	82	1	1	197	9	0	1,033
	4	5	0	101	2	0	9	4	0	20	0	0	141
1960	1	185	0	1,579	1,393	279	4,647	1,697	592	6,821	2,327	686	20,206
	2	127	64	1,448	2,694	1,065	2,679	626	259	582	472	11	10,027
	3	155	105	198	70	22	106	69	6	294	7	0	1,032
	4	1	0	34	9	0	67	0	0	21	2	15	149
1961	1	7	0	144	45	0	2,145	143	0	13,436	234	0	16,154
	2	10	0	1,513	955	2,258	2,186	516	215	3,068	1,683	115	12,519
	3	677	310	359	1,127	1,070	114	1	0	27	9	0	3,694
	4	35	15	18	25	4	32	3	2	30	7	0	171
1962	1	56	0	2,285	825	3	2,413	1,021	24	12,570	2,248	0	21,445
	2	877	0	6,555	5,953	5,900	15,483	1,516	228	1,208	1,63	186	39,537
	3	0—	0—	1,214	120	40	505	4	5	162	92	0	2,142
	4	41	5	134	65	8	124	1	0	256	0	0	634

TABLE 9.—Continued.

Year	Quarter	Regions ¹											Total
		CCI	CCO	SCI	SCO	SCS	BCI	BCO	BCS	SBI	SBO	SBS	
1963	1	7	0	7,543	1,481	73	8,088	5,446	688	8,730	381	184	32,621
	2	1,395	175	3,291	6,132	12,821	1,810	389	42	507	182	86	26,830
	3	0—	0—	180	649	133	187	8	8	305	21	7	1,498
	4	0—	0—	279	161	2	92	3	2	45	0	0	584
1964	1	1,420	0	4,137	3,552	7,213	2,895	133	66	6,678	148	5	26,247
	2	3,056	82	4,524	6,223	3,656	1,063	1	0	384	73	77	19,139
	3	538	125	353	1,814	1,516	1,058	26	15	204	6	0	5,655
	4	0—	0—	945	110	3	71	0	2	81	0	0	1,212
1965	1	16	0	10,145	3,803	669	6,158	1,136	1,013	7,171	396	5	30,512
	2	1,160	0	6,870	7,561	6,219	2,257	424	1,112	6,205	91	17	31,916
	3	75	5	6,304	3,130	3,042	1,056	286	4	866	5	0	14,773
	4	0—	0—	1,037	733	121	185	0	0	15	0	0—	2,091
1966	1	2,973	0	7,078	4,285	409	4,426	275	9	3,289	189	15	22,948
	2	181	0	7,823	9,902	1,164	1,065	63	5	1,023	2	0	21,228
	3	738	56	2,427	960	214	881	36	2	454	90	0	5,858
	4	51	2	1,022	62	14	181	4	0	830	0	0	2,166
1967	1	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
	2	0—	0—	5,646	2,565	367	1,901	59	0	618	23	0	11,179
	3	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0
	4	0—	0—	0—	0—	0—	966	150	8	224	605	0	1,958
1968	1	458	0	3,318	3,259	406	2,342	1,851	0	0—	0—	0—	11,634
	2	4	0	4,020	1,194	697	960	397	0	303	361	0	7,936
	3	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
	4	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
1969	1	919	0	16,404	11,163	1,028	5,712	1,671	5	4,198	588	38	41,726
	2	3	0	5,982	2,364	294	3,459	350	196	612	237	3	13,500
	3	28	91	3,101	678	92	282	13	19	178	13	0	4,495

¹ CCI = Central California inshore
 CCO = Central California offshore
 SCI = Southern California inshore
 SCO = Southern California offshore
 SCS = Southern California seaward
 BCI = Baja California inshore

BCO = Baja California offshore
 BCS = Baja California seaward
 SBI = South Baja inshore
 SBO = South Baja offshore
 SBS = South Baja seaward

The anchovy spawns over a small portion of its range apparently while still schooled; it also spawns over a small portion of the day (25%); it now appears that most spawning takes place just after the full moon, ca. 20% of the lunar month (Smith).⁴ In addition, the spawning behavior is highly seasonal with most spawning occurring in the first half-year. Biases result from sampling during a period in which spawning is occurring (Sette and Ahlstrom, 1948, p. 520), and similar errors may result from missing or oversampling spawning peak periods or dense small patches. Although patches would tend to disperse toward randomness, this process appears to be very slow relative to the duration of the larval stage. Patchiness persists and may

be augmented by predation. For this reason, the samples have been pooled to reduce variance wherever possible. Nevertheless, sample sizes range from zero to tens of thousands of larvae, and a pooled summary may still be based on a chance large sample. In all cases, the above error analysis was done with a sample frequency plot in view and all "outliers" were examined for effect on the sampling question. All samples taken between 1951 and 1960 are listed by frequency distribution in Table 8 for sardine and anchovy total larvae.

Anchovy larvae abundance (Table 9) and sardine larvae abundance (Table 10) for 11 regions and the years 1940, 1941, 1949-69, are listed for each region and quarter in which sampling took place at standard stations. Figure 8 shows the comparison of the regional census estimates and standard haul summations from 1951 to 1966 (Ahlstrom, 1968). The close agree-

⁴ Smith, P. E. Lunar periodicity in the spawning of the northern anchovy (*Engraulis mordax*). Unpublished manuscript filed at National Marine Fisheries Service, Southwest Fisheries Center, P.O. Box 271, La Jolla, CA 92037.

TABLE 10.—Regional census estimates of total sardine larvae (0-: no sampling).

Year	Quarter	Regions ¹											Total
		CCI	CCO	SCI	SCO	SCS	BCI	BCO	BCS	SBI	SBO	SBS	
1940	1	0—	0—	81	343	0—	0—	0—	0—	0—	0—	0—	424
	2	0—	0—	141	210	0—	0—	0—	0—	0—	0—	0—	351
	3	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
	4	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
1941	1	0—	0—	154	211	0—	0—	0—	0—	0—	0—	0—	365
	2	0—	0—	277	313	0—	0—	0—	0—	0—	0—	0—	590
	3	0—	0—	1	5	0—	0—	0—	0—	0—	0—	0—	6
	4	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
1949	1	0	0	0	0	0	9	2	0	0—	20	3	34
	2	0	0	2	11	14	259	1	1	300	2	3	593
	3	304	7	5	12	5	0	0	0	0	0	1	334
	4	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
1950	1	0	0	0	0	0	92	1	0	117	128	2	340
	2	0	2	116	206	128	60	91	3	1,951	402	0	2,959
	3	9	4	3	2	2	1	2	0	10	11	0	44
	4	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
1951	1	0	0	3	0	0	19	4	0	235	63	0	324
	2	0	0	3	89	18	101	103	8	1,313	107	17	1,759
	3	0	0	4	1	0	270	0	0	94	7	0	376
	4	0	0	0	0	0	146	0	0	79	1	0	226
1952	1	0—	0—	1	5	0	117	90	0	464	87	2	766
	2	0	0	27	51	1	95	194	0	427	731	0	1,526
	3	0	0	8	39	0	49	12	0	168	5	0	281
	4	0	0	0	0	0	37	0	0	19	4	0	60
1953	1	0—	0—	0	0	0	48	199	0	342	94	40	723
	2	0	0	1	0	0	73	509	0	123	370	4	1,080
	3	0	0	1	0	0	86	0	0	100	22	0	209
	4	0—	0—	0	0	0	62	0	0	113	2	0	177
1954	1	0	0—	0	1	0	20	185	93	681	51	110	1,141
	2	1	0	80	320	204	355	63	37	290	140	9	1,499
	3	0	0	4	0	0	59	2	0	166	75	0	306
	4	0	0—	0	0	0	5	0	0	239	3	0	247
1955	1	0—	0—	1	2	8	179	278	285	142	110	0	1,005
	2	0	0	35	146	85	72	99	70	14	8	0	529
	3	0	0	1	31	34	228	4	0	34	9	0	341
	4	0	0	0	0	0	18	0	0	64	2	0	84
1956	1	0—	0—	0	0	0	71	58	33	330	54	0	546
	2	0	0	2	173	48	52	11	14	70	93	0	463
	3	0	0	2	43	9	307	0	0	335	0	0	696
	4	0—	0—	1	0	0	0—	0—	0—	0—	0—	0—	1
1957	1	0—	0—	0	0	0	177	1	2	144	12	0	336
	2	0	0	3	188	4	19	3	1	1	0	0	219
	3	0	20	15	0	0	303	0	0	108	0	0	446
	4	0	0	0	38	0	80	0	0	15	3	0	136
1958	1	0	0	83	52	0	259	0	0	224	21	0	639
	2	3	0	52	27	4	9	2	0	12	1	67	177
	3	0	0	26	94	2	287	1	0	217	0	0	627
	4	0	0	0	0	0	9	0	0	1	0	0	10
1959	1	0	0	74	15	3	24	0	0	35	5	0	156
	2	0	0	33	31	1	15	0	0	19	1	0	100
	3	2	0	2	44	0	82	0	0	78	0	0	208
	4	0	0	19	0	0	67	0	0	20	0	0	106
1960	1	0	0	33	13	0	6	0	0	207	0	0	259
	2	0	0	40	7	0	2	0	0	6	0	0	55
	3	0	0	13	0	0	228	81	0	121	2	0	445
	4	0	0	1	0	0	138	0	5	72	0	0	216
1961	1	0	0	0	29	0	1	0	0	54	0	0	84
	2	0	0	7	4	6	0	8	0	73	0	0	98
	3	0	0	14	2	0	90	0	0	17	0	0	123
	4	0	0	15	0	0	8	0	0	295	19	0	337

TABLE 10.—Continued.

Year	Quarter	Regions ¹											Total
		CCI	CCO	SCI	SCO	SCS	BCI	BCO	BCS	SBI	SBO	SBS	
1962	1	0	0	10	0	0	1	0	0	204	0	0	215
	2	0	0	7	7	0	18	0	0	9	2	0	43
	3	0—	0—	26	1	0	240	0	0	56	23	0	346
	4	0	0	1	1	0	14	0	0	109	2	0	127
1963	1	0	0	50	0	0	62	0	0	3	0	0	115
	2	3	0	1	0	0	0	3	0	10	0	0	17
	3	0—	0—	1	0	3	54	0	0	49	0	0	107
	4	0—	0—	7	5	0	96	1	0	31	0	0	140
1964	1	0	0	1	0	0	0	0	0	229	0	0	230
	2	0	0	0	0	0	0	0	0	9	1	0	10
	3	0	0	4	0	0	22	0	0	159	0	0	185
	4	0—	0—	19	0	0	3	0	0	58	0	0	80
1965	1	0	0	2	0	0	5	0	0	7	0	0	14
	2	1	15	0	0	0	3	0	0	0	0	0	19
	3	0	0	7	0	0	4	0	0	429	1	0	441
	4	0—	0—	1	0	0	406	0	0	216	1	0—	624
1966	1	3	0	1	0	0	19	0	0	49	0	0	72
	2	0	0	10	0	0	1	0	0	2	0	0	13
	3	0	0	1	0	0	50	4	0	262	1	0	318
	4	0	0	1	0	0	238	4	0	87	2	0	332
1967	1	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
	2	0—	0—	5	0	0	105	0	0	1,111	0	0	1,221
	3	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
	4	0—	0—	0—	0—	0—	11	0	0	59	0	0	70
1968	1	0	0	0	0	0	0	0	0	0—	0—	0—	0
	2	0	0	2	0	0	5	1	0	0	0	0	8
	3	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
	4	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—	0—
1969	1	1	0	1	1	0	5	1	0	0	0	0	9
	2	0	0	3	0	0	10	3	0	30	0	0	46
	3	0	0	1	0	0	48	0	0	25	3	0	77

¹ CCI = Central California inshore
 CCO = Central California offshore
 SCI = Southern California inshore
 SCO = Southern California offshore
 SCS = Southern California seaward

BCI = Baja California inshore
 BCO = Baja California offshore
 BCS = Baja California seaward
 SBI = South Baja inshore
 SBO = South Baja offshore
 SBS = South Baja seaward

ment between these values lends support to the idea that the method of data assembly causes little bias relative to size of the major fluctuations in anchovy larva abundance. Both the Spearman rank difference and the product-moment correlation coefficients are 0.99.

MacGregor (1968) suggested that the problem of determining the number of batches of eggs spawned per year per female is the major source of imprecision and bias in the adult biomass estimates from egg census and fecundity data. He further suggested that the best strategy for egg census would be to conduct an intensive cruise over a brief period in which no female is likely to spawn more than once. For the purpose of this paper, a preliminary judgment as to the importance of multiple spawnings in the larva ra-

tio estimate of anchovy biomass may be made by comparing three models of spawning behavior. The first model is that the adult biomass is proportional to the regional census estimate. This model assumes that the product of the number of eggs spawned per ton of female, the number of spawnings per year, and the mortality rate of the larvae is stable. The second model is that each anchovy spawns once in the winter quarter. The third model is that each anchovy spawns in the single maximum quarter. Restated, the adult biomass is proportional to the 1) annual average regional census estimate of larval abundance, 2) winter quarter regional census estimate, or 3) annual maximum quarterly regional census estimate. The 1951-66 data for the Ahlstrom standard haul summation, the

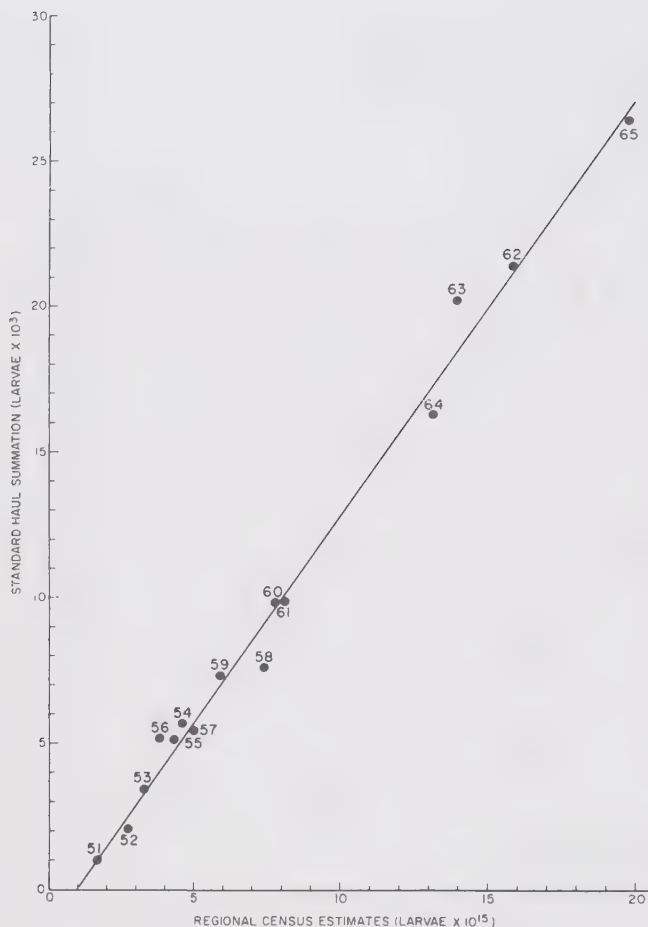


FIGURE 8.—A 16-year comparison of the regional census estimate derived for this paper and the standard haul summation quarterly average (Ahlstrom, 1968).

average regional census estimate, the winter spawning, and seasonal maximum are found in Figure 9. It is clear that the same trend and magnitude of increase are seen from each model. Since there is no obvious difference, the annual average regional census estimate of larva abundance will be used for the current biomass estimates.

It may be seen from Table 9 that the anchovy larvae have increased in number, particularly in the southern California section. Figure 10 illustrates the subdivision of the regional census estimate annual totals by section of the coast from 1951 to 1966. Within the southern California section, the inshore region was the dominant producer of anchovy larvae for the first 7

years. In the next 3 years, the southern California offshore became equally important in numbers of anchovy larvae. Between 1962 and 1965, the seaward region (160-280 miles off the coast) was a very important locality for anchovy larvae and this influence dropped radically to pre-1961 values in 1966 (Figure 11). This change and a smaller one inshore resulted in an appreciable lowering of the overall total in 1966 (Figure 10). The subpopulations of the northern anchovy have been assigned to coastal sections (Vrooman⁶; Vrooman and Smith, 1972),

⁶ Vrooman, A. M. Anchovy subpopulations. Unpublished manuscript filed at National Marine Fisheries Service, Southwest Fisheries Center, P.O. Box 271, La Jolla, CA 92037.

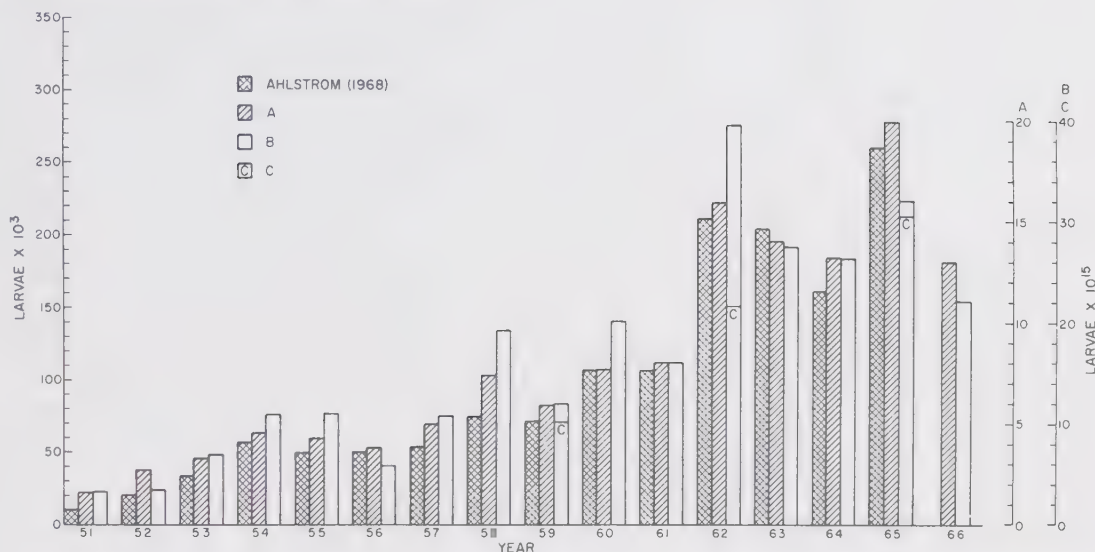


FIGURE 9.—A time-series comparison of the annual quarterly average standard haul summation (Ahlstrom, 1968, double cross-hatch) and the annual quarterly average regional census estimate ("C", clear bar including line C if any).

and the major portion of increase of northern anchovy is ascribed to the "central" subpopulation which spawns off southern California.

The seasonal contribution of anchovy larva abundance from 1951 to 1966 is illustrated in Figure 12. From 1951 through 1959, winter-caught larvae dominated the total. Beginning in 1960, spring larva abundance became increasingly important and, in 1962, substantially exceeded winter larva abundance. As mentioned above, the changing day-length in the spring quarter makes an appreciable difference for which the data have not yet been corrected. The spring-caught larvae are underestimated as a result. No correction has been applied for temperature- or food-specific growth rate changes, by season.

The increase of numbers of anchovy larvae shown in the foregoing regional census estimates could result from the traditional spawning areas being more completely covered with larvae, from new spawning areas being covered, or there being more larvae per unit area. There are instances of all three in the 1951-66 period. In particular, in the southern California section of the coast, where most of the increase took place, the primary effect has been the additional cov-

ering of traditional spawning areas. For example, in the southern California offshore region, April through June, 7 of 50 tows contained anchovy larvae in 1953, 25 of 48 tows contained larvae in 1955, and 51 of 53 tows had anchovy larvae in 1959 (14.0%, 52.1%, and 96.2% respectively). If one fits a regression line to the increasing proportions of positive stations with respect to anchovy larvae off southern California the slopes in percent per year from 1952 to 1966 follow:

	Winter	Spring	Summer	Fall
Inshore (0-80 miles)	1	2	1	1
Offshore (80-160 miles)	4	6	4	1
Seaward (160-280 miles)	2	7	2	1

Also, there are more anchovy larvae per positive station than before. In the years 1962-66 there are 5-8 times as many larvae per positive station as in 1951 (Table 11). The number of larvae per positive station is not independent of the proportion of positive stations. One interpretation of samples of larvae is that they are drawn from relatively small (100's of meters, Smith, in press) patches of larvae which are dispersing in such a way that they tend to overlap. For example, for randomly distributed

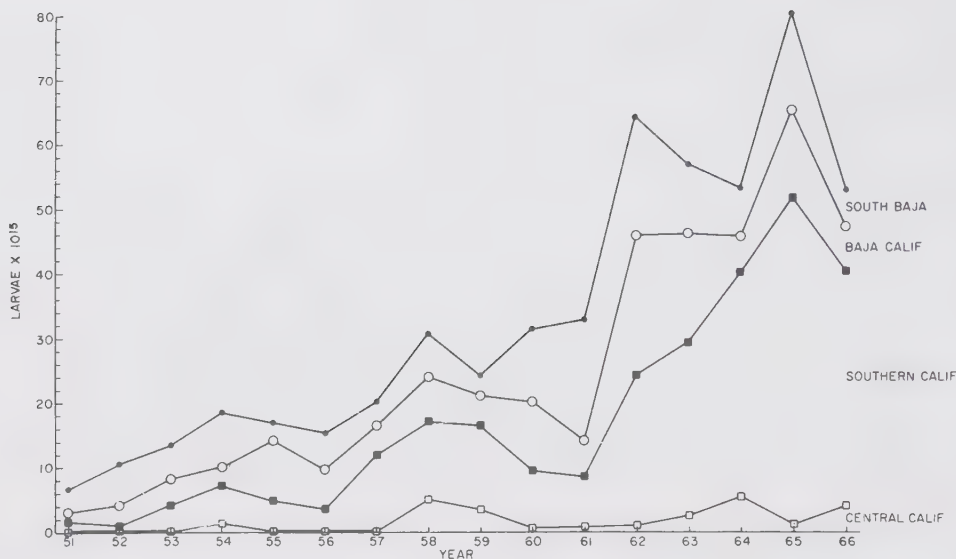


FIGURE 10.—A time-series comparison of the annual total regional census estimates of anchovy larvae as grouped by coastal section. The highest line (solid circle) is comparable to the quarterly average of "A" in Figure 9. The space between the top line and the line with open dots represents the contribution to the total by stations in the south Baja section. The space between the open dot line and the line connecting the solid squares represents the contribution of the Baja California section to the total. The space between the line connecting solid squares and the line connecting open squares represents the contribution of the southern California section. The space between the lines connecting open squares and the abscissa represents the contribution of the central California section to the total. For relative areas of the sections refer to Table 3 and Figure 2.

patches covering 0.1 of the area, the chance of encountering two patches is 0.01; with patches covering 0.9 of the area, the chance of encountering two patches simultaneously is roughly 0.8. In the southern California inshore and offshore regions, the proportion of positive stations is related to the number of larvae per positive station in the following way:

$$\begin{aligned}\log_{10} N_1 &= 3.20 P_1 - 0.218 & t &= 11.17 & 37 \text{ df} \\ \log_{10} N_2 &= 2.13 P_2 + 0.748 & t &= 9.95 & 37 \text{ df} \\ \log_{10} N_3 &= 2.32 P_3 + 0.573 & t &= 14.40 & 76 \text{ df}\end{aligned}$$

where N_i = number of larvae per 10 m² per positive station in the i th region, when $i = 1$ = southern California inshore region, when $i = 2$ = southern California offshore region, when $i = 3$ the inshore and offshore regions are combined;

P_i = proportion of positive stations in winter and spring in offshore ($i = 2$) or inshore areas ($i = 1$), or both ($i = 3$).

If the patchy model applies, this set of equations is good only for the CalCOFI standard tow, in these two regions. For example on theoretical grounds, if the standard tow were to sample under 20 m² rather than the average 3 m² as at present, one would expect the proportion of positive tows to rise and the number per positive tow to decrease for any given average of anchovy larvae per total unit area.

In addition to an increasing proportion of positive tows in traditional spawning areas and increasing numbers of larvae per positive tow, the southern California seaward region is an example of a new spawning area being invaded in

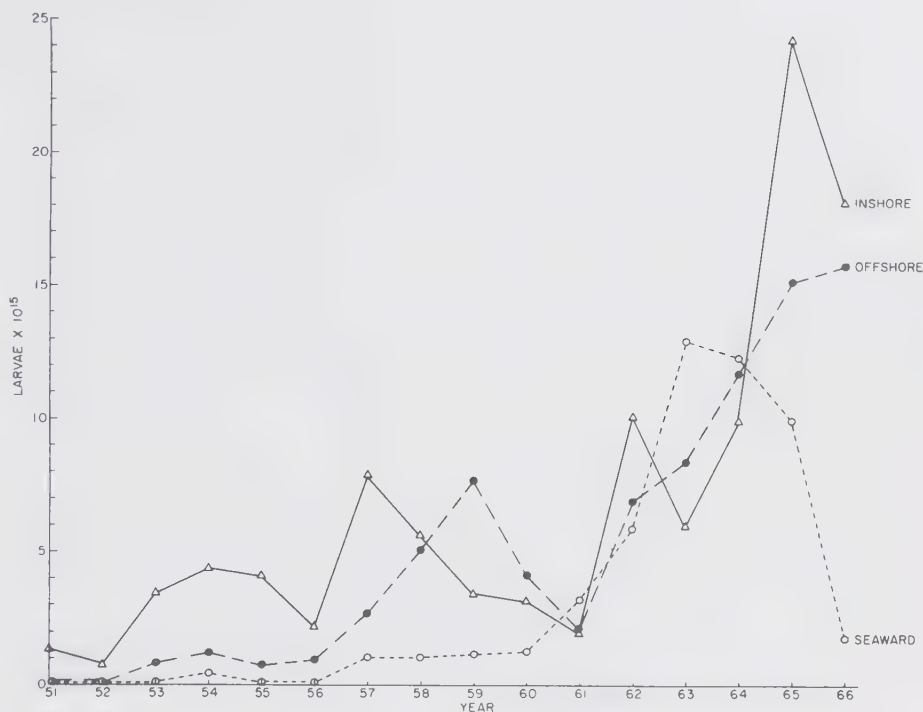


FIGURE 11.—A time-series comparison of the annual total regional census estimates of anchovy larvae as grouped by distance from shore within the southern California section. Lines connecting open triangles represent the southern California inshore, closed circles, the southern California offshore, and open circles, the southern California seaward. For relative areas of the regions refer to Table 3 and Figure 2.

the early sixties and becoming largely unused by the mid-1960's. The incidence of larvae has continued at less than 10% of the 1962 peak year in the southern California seaward region (Table 9).

THE CURRENT ESTIMATE OF ANCHOVY SPAWNING BIOMASS

The practice adopted in this paper for estimating anchovy spawning biomass consists of 1) regression estimates of the relationship between sardine larval abundance and Murphy's estimate (1966) of sardine biomass; 2) the ratio of anchovy:sardine larva abundance until 1958; 3) the regression estimate of the relationship between anchovy larva abundance between 1951 and 1958 and the sardine-derived anchovy bio-

mass; and 4) the use of regression estimates to calculate anchovy and sardine biomass estimates outside the regression period. This differs from Murphy's (1966) method of using an anchovy:sardine ratio for each anchovy estimate. It also differs from Ahlstrom's (1968) method of tying each estimate to the biomass of sardine adults in 1958. Since regressions between two variables with time trends are influenced by the degree of temporal coherence of each variable, caution is warranted in their use. Confidence intervals may be calculated but their meaning is not clear due to the violation of the assumption of independence among the values used to calculate the regression. The regression estimates are used here as a simple shorthand method of reporting an apparent relationship.

The spawner biomass estimates of anchovy and sardine which result from this and previous

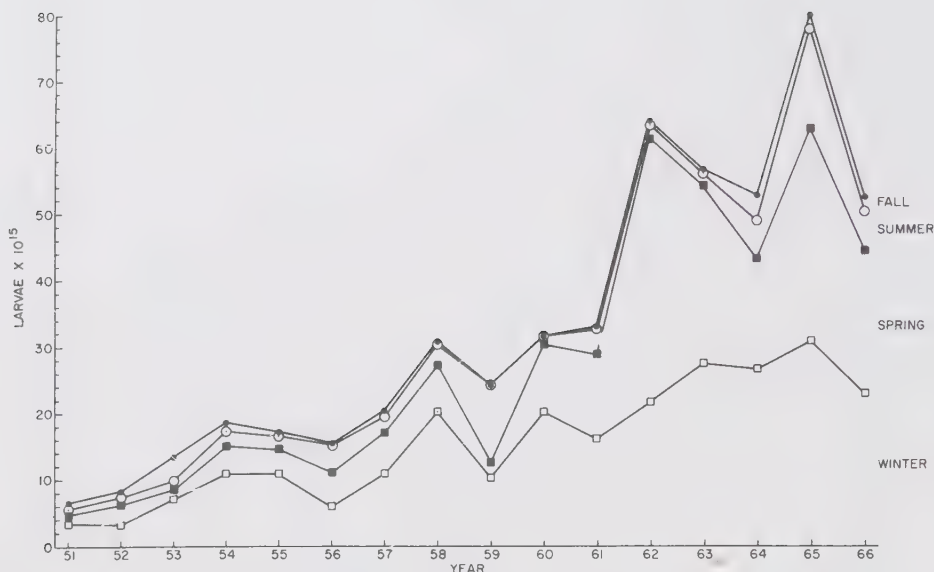


FIGURE 12.—A time-series comparison of the annual total regional census estimates of anchovy larvae as grouped by season of spawning. The highest line (solid circle) is comparable to that found in Figure 10 and to the height of "A" in Figure 9.

studies are found in Table 12. The primary objective of this study concerns the period of increase from 1951 to 1966. Despite various technical deficiencies in the basic data, the years 1940, 1941, 1950, and 1969 are also estimated in the section to follow.

The first column of Table 12, Murphy's (1966) sardine spawner biomass estimates, is reproduced without change. If those estimates are changed by later studies, all other values in the table must be adjusted. The important features of Table 12 are 1) a regression estimate to derive sardine spawner biomass estimates from the regional census estimates of total sardine larvae; 2) a ratio estimate of anchovy spawner biomass which is half the product of the anchovy:sardine ratio and the sardine biomass; and 3) a regression estimate of anchovy spawner biomass derived from the regional census estimate of total anchovy larvae.

The equation for a least squares estimate of sardine spawner biomass and sardine total larvae derived for this study is:

$$B_s = 0.230L_s - 0.057$$

where B_s is the annual estimate of sardine spawner biomass in thousands of short tons and L_s is the regional census estimate annual total of sardine larvae in numbers times 10^{12} in the years 1951-58, excluding 1953. The years 1953 and 1959 were eliminated as outliers on a scatter diagram when it was found that the assumption of constant size distribution of larvae had been violated. The equation was later simplified by assuming a zero intercept to:

$$B_s = 0.206L_s$$

The anchovy spawner biomass estimates were derived from the ratio of anchovy:sardine larvae and the Murphy sardine biomass estimate in the following way:

$$B_a = c \left(\frac{L_a}{L_s} B_s \right)$$

where B_a is the ratio estimate of anchovy spawner biomass, L_a is the regional census estimate

TABLE 11.—Anchovy larvae per positive station.

Year	No. of positive stations	No. of anchovy larvae	No. of larvae per positive station
1951	344	26,951	78
1952	399	53,457	134
1953	539	85,178	158
1954	626	126,191	202
1955	558	134,017	240
1956	482	104,192	216
1957	518	135,966	262
1958	667	197,082	295
1959	729	182,176	250
1960	628	254,263	405
1961	420	88,925	258
1962	374	190,735	510
1963	370	172,611	466
1964	372	141,498	380
1965	392	234,850	599
1966	738	364,689	494

of anchovy total larvae, and c is a constant representing the relative fecundity of sardine relative to anchovy, here assumed to be approximately 0.5. Lenarz (1972) suggests a constant of escapement of 1.1 to counteract the tendency for anchovy larvae to pass through the mesh openings of the standard silk net to a greater extent than sardine larvae. This experimentally derived estimate from paired tows which captured both species in standard and fine mesh

nets is considered too small to be appreciable on the scale of variability encountered in plankton tows. Murphy's (1966) estimate of the escapement factor, i.e., 2, is rejected.

The equation for a least squares estimate of the anchovy spawner biomass and anchovy total larvae is:

$$B_a = 0.094 L_a + 0.072$$

defined in the same way as the sardine case above. Similarly, the zero intercept was forced, giving:

$$B_a = 0.098 L_a$$

which is the equation used for the regression estimate of anchovy spawner biomass.

The aberrant years 1953 and 1959 were recalculated assuming the slope and the Murphy sardine spawner biomass estimate are correct and that the sardine larva estimates are biased or imprecise. The recalculated estimates (parentheses, Table 12) appear to conform better to the trends of anchovy biomass and anchovy-sardine ratio.

The data from 1940, 1941, 1950, and 1969 have been manipulated to extend the biomass estimates. The 1940 and 1941 cruises were

TABLE 12.—Sardine and anchovy spawner biomass estimates by ratio and regression methods.

	Murphy sardine spawner biomass ($\times 10^3$ T)	Regression sardine spawner biomass ($\times 10^3$ T)	Sardine larval estimate ($\times 10^{12}$)	Anchovy larval estimate ($\times 10^{12}$)	Anchovy sardine ratio	Ratio anchovy spawner biomass ($\times 10^3$ T)	Regression anchovy spawner biomass ($\times 10^3$ T)
1940	1,296		1,634*	5,943*	3.64	2,359	
1941	2,001		2,476*	7,104*	2.87	2,871	
1950	716		3,343	2,602	0.78	279	
1951	570	553	2,685	6,504	2.42	690	637
1952	554	542	2,633	8,132	3.09	856	797
1953	709	450	2,189 (3,442)**	13,632	6.23 (3.96)**	2,209 (1,404)**	1,335
1954	668	658	3,193	18,533	5.80	1,937	1,816
1955	425	404	1,959	17,100	8.73	1,855	1,676
1956	293	351	1,706	15,215	8.92	1,307	1,491
1957	212	234	1,137	20,040	17.63	1,869	1,964
1958	281	299	1,453	28,272	19.46	2,875	2,771
1959	190	117	570 (922)**	23,463	41.16 (25.45)**	3,910 (2,418)**	2,299
1960		201	975	31,414	32.22		3,079
1961		132	642	32,538	50.68		3,189
1962		151	731	63,758	87.22		6,248
1963		78	379	61,533	162.36		6,030
1964		104	505	52,253	103.47		5,121
1965		226	1,098	79,292	72.21		7,771
1966		151	735				
1969		27†	132†	52,200	71.02		5,116
				33,623†	254.72†		3,293†

* 1940, 1941—larval estimates seasonally adjusted.

** Parenthetic numbers for 1953 and 1959 assume larval numbers biased.

† 1969—larval counts 75% complete; adjusted for extra retention of small larvae.

conducted during the sardine spawning season, but excluded an important portion of the anchovy spawning season. Similarly, the cruises only sampled 20% of the area we now consider routinely surveyed. The ratio of sardine and anchovy larvae was used for 1950 and will not be discussed further. The 1969 samples systematically violated the assumption of stable size composition of larvae.

The cruises of 1940 and 1941 were conducted over the southern California inshore and offshore regions in the spring and summer. The total for both species in both regions and in both years was derived by simulation of analogous cruises within the 1951-60 survey period and the product-moment correlation coefficient is listed for each species, for each region, and year.

Year	Species	Region	Original	Seasonally adjusted	Correlation coefficient
1940	Anchovy	SCI	1,545	3,229	0.794
		SCO	820	2,714	0.945
		Total	2,365	5,943	
1940	Sardine	SCI	502	726	0.794
		SCO	891	908	0.955
		Total	1,393	1,634	
1941	Anchovy	SCI	1,494	3,257	0.845
		SCO	2,104	3,847	0.962
		Total	3,598	7,104	
1941	Sardine	SCI	987	1,305	0.807
		SCO	1,161	1,171	0.981
		Total	2,148	2,476	

The ratio of this group of samples, within the same boundaries as the other regional census estimates used here, change from 1.70 to 3.64 in 1940 and change from 1.68 to 2.87 in 1941. Accordingly, these ratios are used in Table 12.

The 1969 data point for anchovy is modified in a crude attempt to adjust for the extra retention of anchovy larvae in a new sampling net (see Figure 4) which retains approximately 50% more larvae. The 1969 surveys were conducted with a 1-m net with 50% more open area, more regular mesh apertures, and an average mesh width of 0.505 mm rather than the 0.55 mm aperture silk net (used and wet). The effect of additional mesh on reducing the extrusion effect of filtration pressure is discussed in Tranter and Smith (1968).

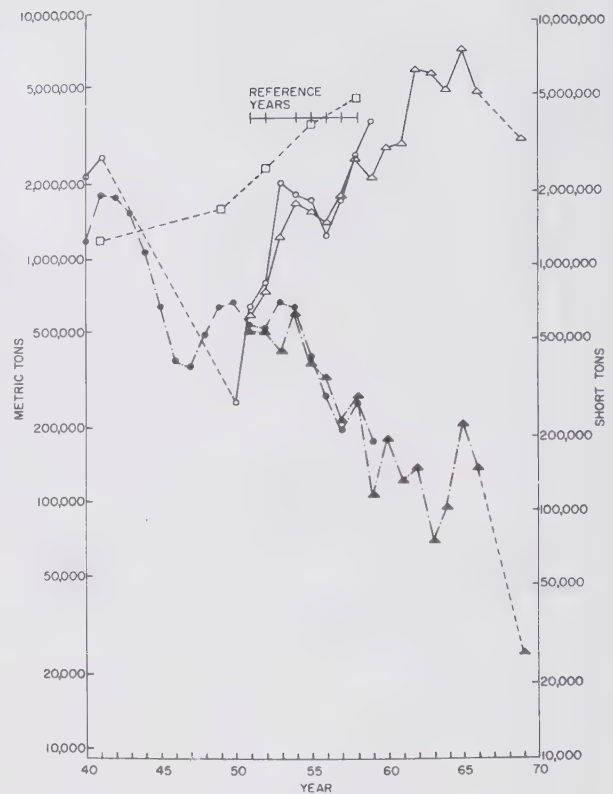


FIGURE 13.—A time-series comparison of sardine and anchovy biomass estimates from 1940 through 1969. The solid circle represents sardine biomass as calculated from the fishery by Murphy (1966) and extends from 1940 to 1959. The solid triangle represents sardine biomass derived from a regression estimate of the relationship between the Murphy biomass estimate and the annual total regional census estimate of sardine larvae during the reference years and is extended from 1951 through 1969. The open circle represents the estimates of biomass derived from the ratio of anchovy larvae to sardine larvae and the Murphy sardine biomass estimate from 1940 to 1959. The open triangle represents anchovy biomass derived from a regression estimate of the relationship between the anchovy tonnage calculated from the anchovy:sardine larvae ratio, and the annual total regional census estimate of anchovy larvae and extends from 1951 through 1969. The open squares represent the Murphy estimate of anchovy spawning biomass by 3-year averages (Murphy, 1966, Figure 17, p. 65). Dashed lines represent interpolations between non-adjacent years.

Figure 13 contains all the estimates resulting from this study. Murphy's sardine biomass estimates are plotted from 1940 to 1959. The anchovy biomass estimates derived from the anchovy sardine ratio and the anchovy larva regional census in 1940, 1941, and 1950 through 1959. The regression estimates are reproduced from 1951 to 1959 for comparison with the Murphy sardine biomass and ratio-derived anchovy biomass. The regression estimates of both sardine and anchovy spawner biomass are extended through 1966 and a tentative estimate for 1969 is placed for comparison.

DISCUSSION

Important changes in the size of the anchovy population have occurred in the California Current area over the past two decades. The increase of anchovy has coincided with the continuing decrease of sardine in the same area. All available evidence indicates that the anchovy and sardine populations declined between 1941 and 1951, and thereafter the anchovy underwent a sustained increase reaching a plateau of 5-8 million metric tons between 1962 and 1966. This population size may be between 2 and 3 times the anchovy spawning population of 1940-41 and between 5 and 10 times the anchovy population in 1950-51. Changes of this magnitude in the absence of a fishery underscore the importance of natural fluctuations in the population size of a fish species. Fishery management of such a species must be responsive to changes of this magnitude and rapidity.

Murphy (1966, 1967) speculated on the effect of the anchovy population on the recovery of the sardine population. Neither the feeding of anchovy and sardine nor the population dynamics of the food organisms is well enough understood in the California Current. Since the size frequency curves of larvae are relatively invariable (Ahlstrom, 1965; Lenarz, in press) one would expect competition, if any, to occur in the juveniles and pre-recruits of either species.

One interesting fact may be the decline of sardine spawning in the spring and summer has coincided with an increase of spawning in spring

by the anchovy. In the estimates of spawner biomass of sardine and anchovy, no attention has been given the possibility that fecundity in numbers of eggs per batch and number of batches per unit time is plastic.

The numbers of anchovy and sardine larvae have been used here exclusively to describe changes in the adult biomass which spawned them. Since this process seems so effective, one might wonder what is required to refine techniques so that spawning, and larval and juvenile survival, may be used to predict the recruitment of year classes to the fishery. I believe the two major barriers are that 1) the size composition of the larvae of both species is so dependent on the sampling gear that mortality rates will remain too crude to project survival and 2) the effect of transport of larvae, particularly offshore to "unfavorable" areas, is neither well enough measured nor understood to effect predictive sampling systems.

ACKNOWLEDGMENTS

I would like to acknowledge the impact on my personal research and the effect on the overall study of environmentally induced natural variability that Dr. O. Elton Sette has had. The preparation of this paper would not have been possible without the aid and discussions of Dr. E. H. Ahlstrom. I would like also to acknowledge the assistance of my colleagues Dr. William Lenarz, David Kramer, and James Zweifel in compiling and editing this paper. Drawings and mathematical tables were prepared by James Thrailkill, Esther Barker, and Nancy Wiley. All biological specimens used were sorted and identified since 1940 by Dr. E. H. Ahlstrom and his staff.

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APPARENT ABUNDANCE OF SOME PELAGIC MARINE FISHES OFF THE SOUTHERN AND CENTRAL CALIFORNIA COAST AS SURVEYED BY AN AIRBORNE MONITORING PROGRAM

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ABSTRACT

From September 1962 through December 1969, commercial aerial fish spotter pilots estimated tonnage of species observed during flights off the southern and central California coast. Observations of fish and the aircraft's flight route were recorded on special charts. These data were analyzed using 10-minute-longitude by 10-minute-latitude "block areas." A total of over 17,593 flight hours was involved, surveying 57,628 block areas—37,186 during the day and 20,442 during the night. Data from each block area were used to compute diurnal and nocturnal variation in apparent abundance and an annual index of apparent abundance.

Pacific bonito, *Sarda chiliensis*, and yellowtail, *Seriola dorsalis*, were observed in greater frequency and quantity during the day, and the northern anchovy, *Engraulis mordax*; jack mackerel, *Trachurus symmetricus*; and Pacific mackerel, *Scomber japonicus*, were observed in greater frequency and quantity during the night. Pacific barracuda, *Sphyraena argentea*, was observed in greater quantity at night but more frequently during the day.

Between 1963 and 1969 indexes of apparent abundance declined for jack mackerel, Pacific mackerel, Pacific sardine, Pacific bonito, Pacific barracuda, and yellowtail and increased slightly for the northern anchovy. The index closely follows estimates of total abundance for the Pacific mackerel, a species for which reliable estimates of total abundance are available. From observations of the catch trends in the bonito fishery, the index appears to be little affected by changes in economic demand. Its trends in apparent abundance are evident before they are reflected in catches and are useful in the evaluation of catch variations in underutilized resources.

In a search for more efficient fishing methods, many of the fisheries throughout the world that catch pelagic surface schooling species are using aircraft to locate and guide the fleet to the schools and in some cases to direct the catching operation (Cushing, Devold, Marr, and Kristjonsson, 1952). In some areas of the United States the services of the fish spotter are vital to the success of the commercial fleet which depends in part on the aircraft scouting the fishing grounds to obtain current information on the location of near-surface schooling fish (Squire, 1961). At times commercial aerial fish spotters assist the

sport fishing fleet by advising them of the location of desirable marine game species.

Data obtainable by techniques of aerial observation have been used by fishery biologists to gain information on distribution and abundance of pelagic near-surface schooling fish.

Sette (1949) investigated the possibilities of aerial scouting for sardines off southern California in search of a method that would provide information useful in estimating abundance yet be free of the availability influence. Aerial scouting was conducted during the day, and commercial fishing was conducted at night. As a result the spotting data were deemed less reliable than those obtained from the commercial fishery.

Jones and Sund (1967), using commercial fish

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spotter aircraft in a search for tuna schools in the same area surveyed by a research vessel, found that the aircraft was about two and one half times more efficient than the vessel at locating fish schools. An evaluation of aircraft by the U.S. Navy, for making biological observations, indicated that for whales the frequency of sighting averaged about 20 times greater than that from ships (Levenson, 1968).

From 1956 to 1964 the California Department of Fish and Game conducted monthly survey flights along the California coast from San Francisco to Mexico. Data were published as flight reports in chart form showing the aircraft's flight track, areas surveyed, notes on species observed, and number of schools and their geographical location. Large variations in the number of schools visible over a short-time period appeared to limit the usefulness of the data, and the surveys were discontinued in 1964. The average number of schools sighted per flight was determined by Wood (1964),² and from these data a comparison was made of the relative abundance of northern anchovy, *Engraulis mordax*, schools for the period 1956 through 1963. Limitations on flights to nearshore areas during daylight and low search time in any one area restricted the potential of these surveys for determining the apparent abundance of the many pelagic species found off the California coast.

Fish spotter aircraft range over a large geographical area, and during these flights they may observe concentrations of several species of pelagic fish. Many times these fish are not caught for one or more reasons, such as fishing boats not equipped with proper nets, concentrations are small, species is not economically desirable, and fishing boats are not capable of reaching fish within a reasonable length of time. However, the fish spotters are able to identify these concentrations of fish.

Species commonly observed by the aerial fish spotters within the survey area were northern anchovy, jack mackerel, *Trachurus symmetricus*; Pacific bonito, *Sarda chiliensis*; Pacific mack-

erel, *Scomber japonicus*; Pacific sardine, *Sardinops sagax*; bluefin tuna, *Thunnus thynnus*; Pacific barracuda, *Sphyrna argentea*; white seabass, *Cynoscion nobilis*; and yellowtail, *Seriola dorsalis*.

The majority of fish spotting effort is directed toward the location and catching of jack mackerel, Pacific mackerel, Pacific bonito, Pacific sardine, and in recent years the northern anchovy. Of these five species the Pacific sardine and Pacific mackerel are most economically desirable with jack mackerel, Pacific bonito, and northern anchovy of descending importance.

To increase knowledge on the apparent abundance of pelagic near-surface marine life, the Tiburon Marine Laboratory initiated a pelagic fish monitoring program in cooperation with aerial fish spotter pilots who are active in spotting for the southern and central California coastal commercial fishery. These cooperators were individuals with specialized training and experience. When assisting the commercial fleet, fishing success is dependent upon accurate identification of schooling species by the spotters. They have considerable experience in estimating the weight of fish schools, and they are considered to be quite accurate in the estimation of weight.

There are a number of variables that affect the statistical accuracy of fish spotter data which are difficult to evaluate, such as individual difference in ability of pilots to locate fish, determine species, and estimate school size, and estimate total tonnage available in a fishing area. Variation in estimating school size probably has more effect on the data than the other variables. However, since at least five experienced observers were used in the program during each year, it was assumed that reasonable annual averages were obtained.

This report consists of an analysis of aerial fish spotter data for the period September 1962 through December 1969 to determine if, for the species commonly observed, it can be used to: (1) compute an accurate index of apparent abundance and (2) obtain a trend in the apparent abundance of pelagic near-surface species and in particular those of underutilized resources.

² Wood, R. 1964. Aerial surveys along the California coastline 1956 to 1963. Document V prepared for the Marine Research Committee meeting, March 6, 1964, San Pedro, Calif., 2 p. [Processed.]

METHODS AND PROCEDURES

Five fish spotter pilots were contracted to record observations of pelagic species, giving location, number of schools, estimated tonnage of each school or groups of schools, counts of large marine animals, and flight track for each survey flight. Two pilots usually covered the Santa Barbara Channel and Santa Barbara Islands north to Estero Bay and occasionally into Monterey Bay. The remaining three spotter pilots normally surveyed the area from west of Los Angeles to southwest of San Diego and occasionally offshore to San Clemente Island, Cortez Bank, and San Nicholas Island. Flight operations were conducted during daylight hours or on nights during the dark phase of the moon at elevations of 500 to 1,200 ft (152 to 365 m) above the sea surface.

TECHNIQUES OF OPERATION

Specific observation of a fish school has three phases: (1) distinguishing a school, (2) identifying the species, and (3) estimating weight of the school. The detection of near-surface schools during the day is dependent upon the pilot's ability to distinguish subtle color and light intensity differences in the water. Detection of schools at night is possible only during the dark period of the moon and depends on the pilot's ability to discern gradation of light intensity. Bioluminescence of planktonic organisms agitated by schooling fish indicates by a dull glow the location and size of the school. Species are identified during the day on the basis of a combination of two or more of the following characteristics: color of school or individual fish, shape of school, and behavior and size of individuals within the school. At night, species identification is based on shape of the luminous area and behavior of the schooling fish under undisturbed conditions, or by the behavior of the school after being subjected to a stimulus from an external source such as a flash from the aircraft's landing light.

At first observations were recorded by the pilots on small portable tape recorders. This

method was unsatisfactory, and recorders were replaced with three charts covering the coastal waters from the Coronado Islands, Mexico, north to Half Moon Bay, Calif. The charts were completed by the pilots after each flight and were submitted quarterly to the National Marine Fisheries Service. Figure 1 illustrates the type of information recorded by the fish spotter pilot.

PROCESSING OF OBSERVATION DATA

Each chart was overlaid with a 10-minute-longitude by 10-minute-latitude grid, numbered according to the California Department of Fish and Game "Block area" statistical system (Clark, 1935). With the gridded chart, the observation and flight track data could be conveniently tabulated and coded for subsequent computer analysis. California Department of Fish and Game statistical code numbers were assigned to each of the 27 species of marine animals observed. The computer output grouped data by species, year, week, block area, day or night observation, number of schools, tons per school, and tons per block area. The data for block areas were later combined into 11 larger grouped block areas or "zones" lettered A through K (Figures 2 and 3). These zones were selected to outline important geographical areas where fish were commonly observed.

The following criteria were used in tabulating the data from the flight charts:

1. Groups of schools which were indicated on the flight chart as covering more than one block area were listed for each block holding part of the group. For example, if one group of schools (10 schools, 15 tons per school, total 150 tons) overlapped two block areas equally, each area was credited with having 5 schools at 15 tons per school, equalling 75 tons per block area.

2. If only one school was shown overlapping two block areas, the school was assigned to the block area having the greatest portion of the school.

3. If a large area of fish was indicated involving more than two block areas and only a total tonnage estimate made, the tonnage was credited to the block areas in proportion to area outlined.

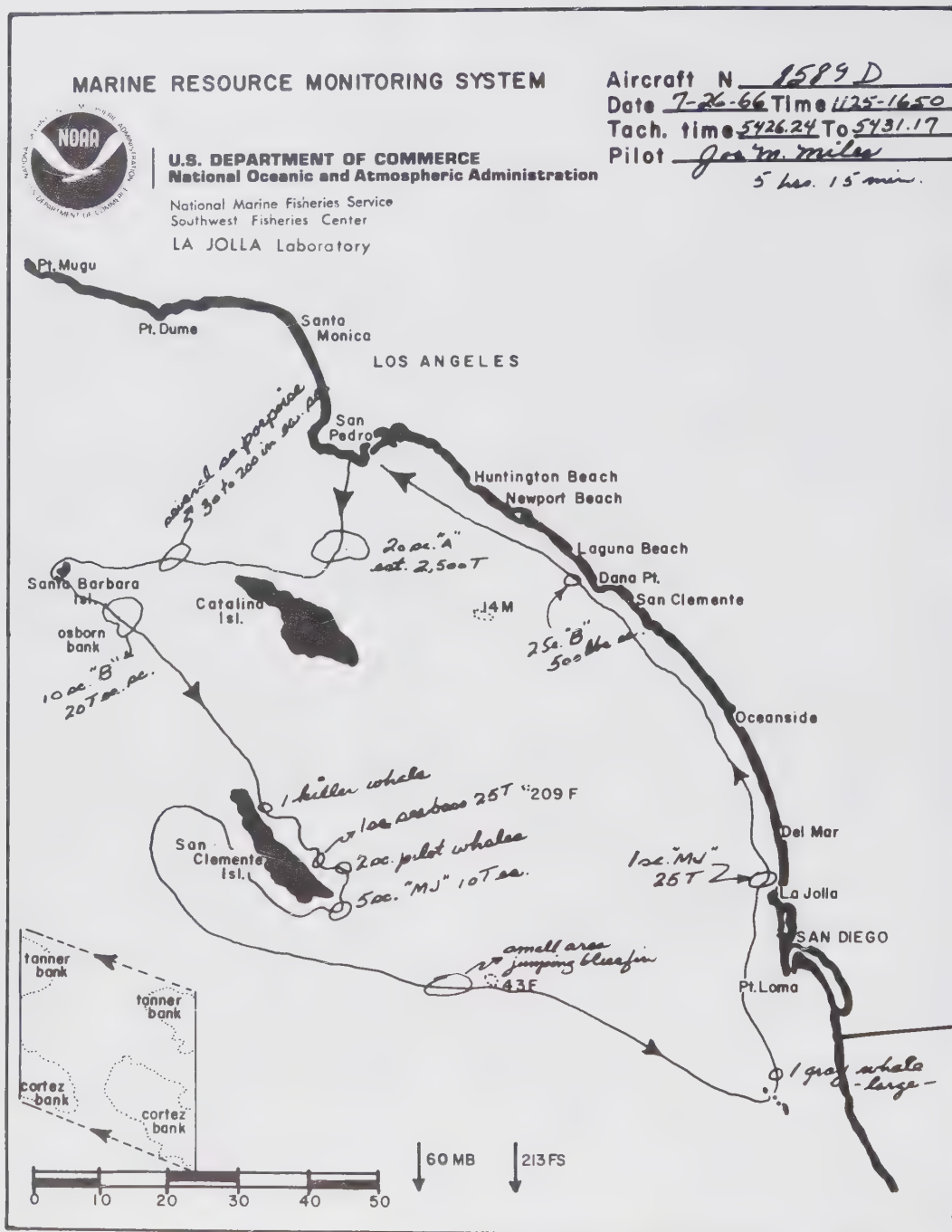


FIGURE 1.—Flight chart for southern California area showing typical flight track and fish and mammal observations. Block area grid is overlaid on chart for coding observations.

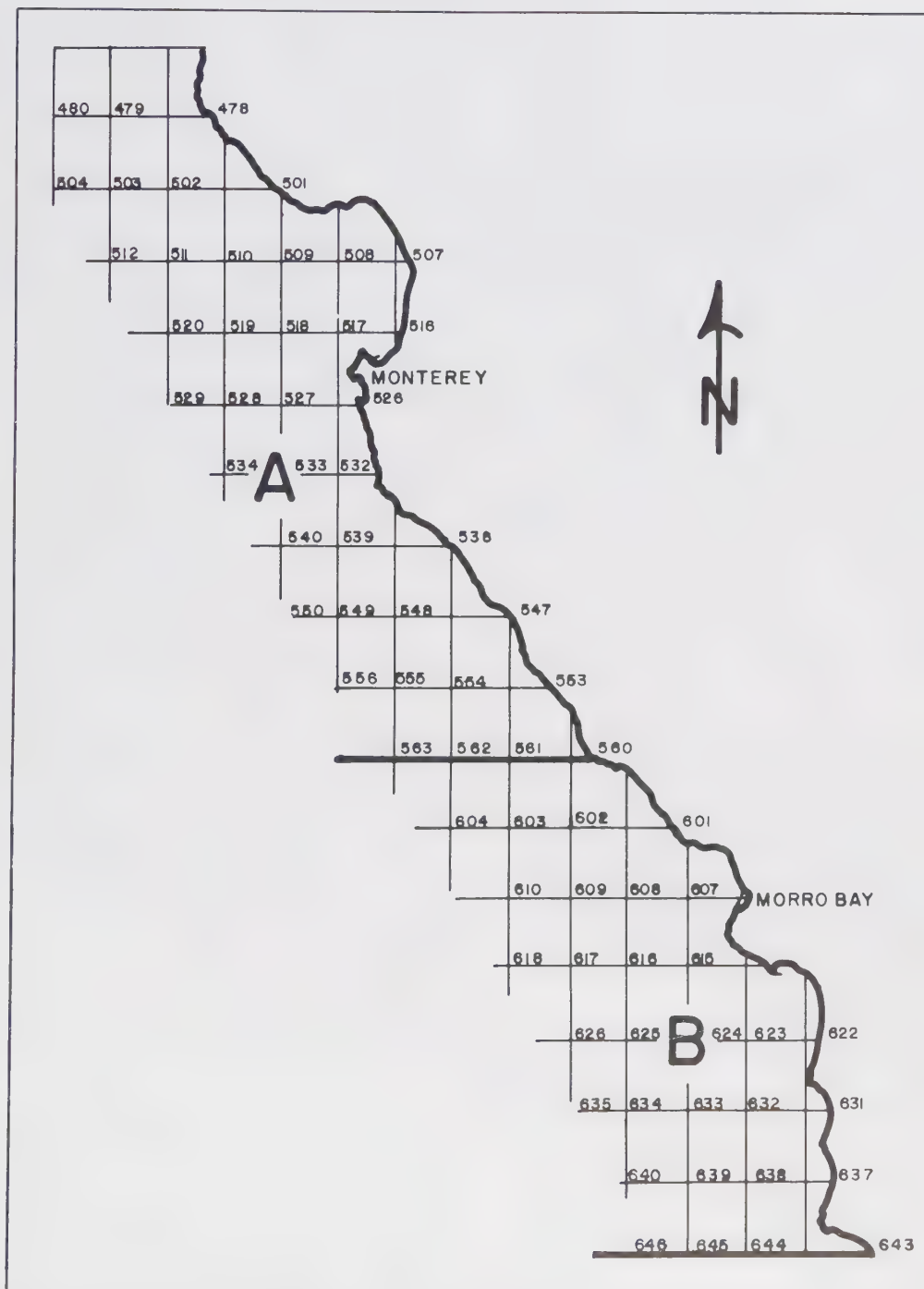


FIGURE 2.—Block areas grouped into zones (A-B), selected to outline the more important coastal fishing areas.

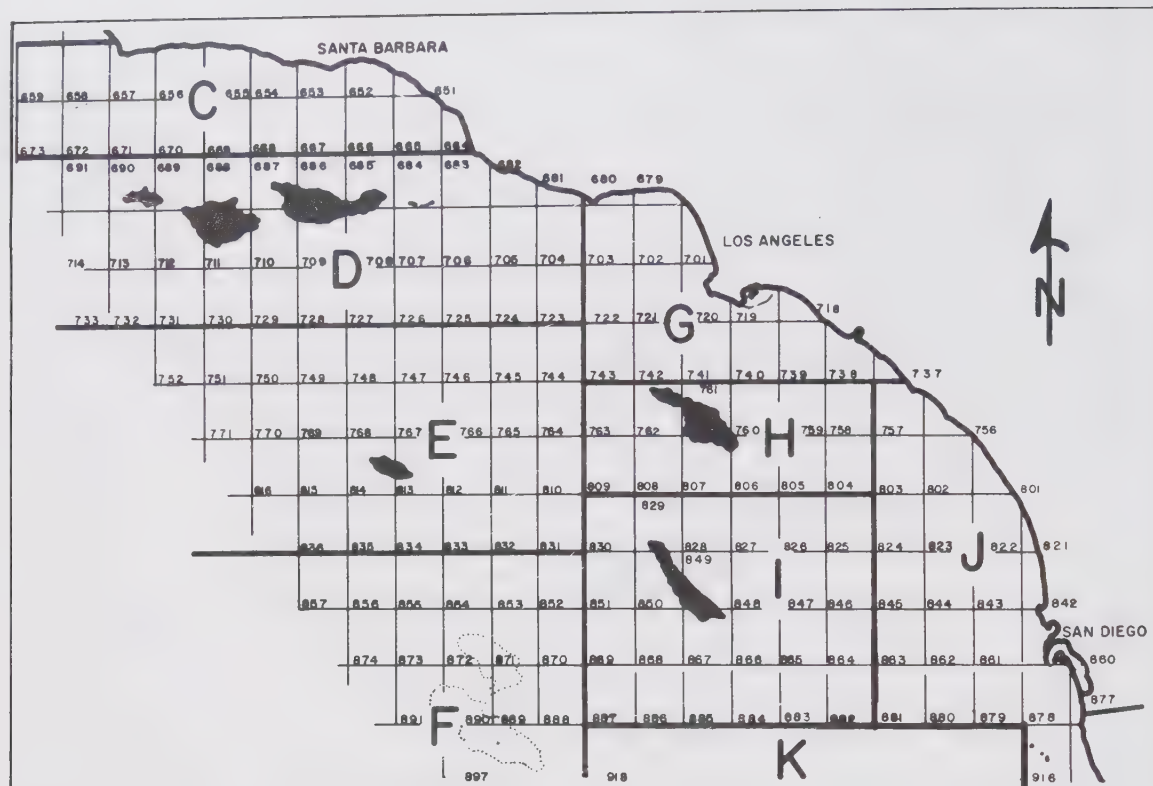


FIGURE 3.—Block areas grouped in zones (C-K), selected to outline the more important coastal fishing areas.

4. Whales, porpoises, and sharks were recorded as numbers of individuals observed.

5. When the flight track entered any portion of a block area, the block area was credited for the purpose of determining observation effort as having a "block area flight."

RESULTS

During survey flights, 20 species of fish were observed and identified. A number of other marine species (mammals, invertebrates) were observed and all are listed in Table 1.

DISTRIBUTION OF FLIGHT OBSERVATION EFFORT

A total of 17,593 flight hours were logged by spotter pilots during the survey period. The number of block area flights from September

1962 through the end of 1969 totaled 57,628 with 37,186 block areas surveyed during the day and 20,442 at night. Distribution of day and night block area flights by year and by zone is shown in Table 2.

NOCTURNAL AND DIURNAL VARIATION IN NUMBER OF SIGHTINGS AND TONNAGE

To determine criteria concerning the frequency of observation during the day and night for each of the species more commonly observed, the ratios in numbers of sightings and tonnages observed were calculated for the period September 1962 through December 1966. Information on the diurnal and nocturnal frequencies and magnitude of occurrence for each species is of importance in evaluating which observation (day

SQUIRE: PELAGIC MARINE FISHES OFF SOUTHERN AND CENTRAL CALIFORNIA

TABLE 1.—Species of fish and other marine animals observed during surveys.

Fish:	
Basking shark (<i>Cetorhinus maximus</i>)	
White shark (<i>Carcharodon carcharias</i>)	
Northern anchovy (<i>Engraulis mordax</i>)	
Pacific sardine (<i>Sardinops sagax</i>)	
Pacific bonito (<i>Sarda chiliensis</i>)	
Jack mackerel (<i>Trachurus symmetricus</i>)	
Pacific mackerel (<i>Scomber japonicus</i>)	
Pacific barracuda (<i>Sphyræna argentea</i>)	
Yellowtail (<i>Seriola dorsalis</i>)	
White seabass (<i>Cynoscion nobilis</i>)	
Bluefin tuna (<i>Thunnus thynnus</i>)	
Albacore tuna (<i>Thunnus alalunga</i>)	
Yellowfin tuna (<i>Thunnus albacares</i>)	
Skipjack tuna (<i>Katsuwonus pelamis</i>)	
Jacksmelt (<i>Atherinopsis californiensis</i>)	
Ocean sunfish (<i>Mola mola</i>)	
Striped bass (<i>Morone saxatilis</i>)	
Pacific saury (<i>Cololabis saira</i>)	
Swordfish (<i>Xiphias gladius</i>)	
Striped marlin (<i>Tetrapturus audax</i>)	
Mammals:	
Gray whale	
Pilot whale	
Blackfish (killer whale)	
Porpoise and dolphin	
Seals and sea lions	
Invertebrates:	
Squid	
Jellyfish	

or night) might be the more significant in evaluating the trend of apparent abundance. These data were calculated during an earlier part of the study (1962-1966) to evaluate the method of using aerial fish spotter data.

The total amount of fish estimated to have been seen by the aerial fish spotters during the period 1962-1966 was 5,289,521 tons of the following species: northern anchovy, 4,550,218 tons; jack mackerel, 335,794 tons; Pacific bonito, 238,247 tons; Pacific mackerel, 103,464 tons; and yellowtail, 1,955 tons.

Annual sightings of each species per block area flight were expressed as a percentage of all block area flights day and night (% day/% night) and are shown in Table 3. The ratio of diurnal and nocturnal sightings was obtained by dividing the percentage of day sightings by the percentage of night sightings. Ratio values greater than 1.00 indicate a greater number of sightings during day, less than 1.00 indicate greater number of sightings during the night.

To determine the day and night differences in the tonnage observed for each species, the

TABLE 2.—Observation effort (day/night) in block area flights by zone for the period September 1962 through 1969. [Data are presented in number of block area flights (day/night).]

Zone	1962	1963	1964	1965	1966	1967	1968	1969	Total
A	41/62	175/78	125/86	102/84	239/9	361/0	585/0	86/29	1,714/348
B	174/117	220/75	283/156	471/252	770/90	610/13	519/0	126/10	3,173/713
C	104/126	470/658	632/680	892/743	1,860/495	1,016/559	1,014/281	2,130/718	8,118/4,260
D	12/71	137/167	409/518	485/434	1,268/385	813/533	1,000/291	1,942/712	6,066/3,111
E	0/10	63/96	40/263	48/58	108/30	40/51	101/109	87/97	493/714
F	0/6	15/32	23/37	2/106	37/21	15/53	35/194	79/48	206/497
G	0/2	454/496	394/610	481/404	1,358/434	874/596	616/676	735/1,500	4,939/4,718
H	0/0	291/282	363/336	387/349	723/206	435/305	368/469	303/576	2,870/2,523
I	0/0	366/155	477/157	395/258	814/208	614/281	544/378	613/348	3,823/1,785
J	0/0	463/198	586/300	550/128	847/113	1,087/154	672/294	932/188	5,137/1,375
K	0/0	18/0	13/0	13/0	69/9	65/10	75/32	106/1	350/52
Total	331/394	2,672/2,237	3,336/3,143	3,826/2,816	8,120/2,000	5,936/2,555	5,826/3,070	7,139/4,227	37,186/20,442
Grand total	725	4,909	6,479	6,642	10,120	8,491	8,896	11,366	57,628

TABLE 3.—Annual sightings per block area flight in percentage (day/night) and day/night averages and ratios.

Species	1962	1963	1964	1965	1966	Day/night	
						Average	Ratio
Northern anchovy	3.3/21.6	8.7/19.7	7.8/21.5	4.9/11.8	5.4/25.0	6.0/19.9	0.30
Pacific bonito	6.3/ 6.3	7.3/ 5.1	9.7/ 3.4	8.3/ 1.7	6.3/ 2.5	7.5/ 3.8	1.99
Jack mackerel	0.3/ 1.0	3.5/ 9.9	5.0/ 6.7	3.3/ 6.2	1.8/ 5.7	2.7/ 6.1	0.47
Pacific mackerel	0.0/ 6.9	4.2/ 9.6	2.0/ 3.5	0.3/ 1.2	0.1/ 2.0	1.3/ 4.6	0.28
Pacific sardine	1.2/ 1.5	1.5/ 2.3	0.8/ 2.1	0.1/ 0.4	0.2/ 0.4	0.7/ 1.3	0.57
Yellowtail	0.0/ 0.0	1.0/ 0.4	0.2/ 0.0	0.2/ 0.0	0.2/ 0.0	0.3/ 0.0	4.00
Pacific barracuda	1.8/ 0.0	0.9/ 0.6	0.5/ 0.6	0.7/ 0.0	0.2/ 0.1	0.8/ 0.2	3.15

amount observed (day or night) in each zone was divided by the number of block area flights (day or night) within the zone. The average number of tons observed per block area flight for each zone, the average number of tons observed for all zones combined, and ratios of day and night tonnages observed are shown in Table 4. Ratios were obtained by dividing the tons per block area flight (day) by tons per block area flight (night). Therefore, ratios greater than 1.00 indicate greater tonnage during the day, less than 1.00 indicate greater tonnage during the night.

AVERAGE WEIGHT OF FISH SCHOOLS

Average weight of schools was computed for the period September 1962 through December 1966 from all data having estimates of individual schools by weight. As previously indicated, some tonnages were given by areas, not by numbers of schools and tonnages of each school. The average tonnage per school is listed for each species in Table 5.

INDEX OF ANNUAL APPARENT ABUNDANCE

An index of annual apparent abundance was calculated for observations during day and night for each zone and for all zones combined from September 1962 through December 1969 for the northern anchovy, Pacific bonito, jack mackerel, Pacific mackerel, Pacific sardine, yellowtail, and Pacific barracuda. Marr (1951) defined the term apparent abundance as "abundance as affected by availability, or the absolute number of fish accessible to a fishery." This definition of apparent abundance most nearly describes the type of index calculated in this paper.

For convenience in calculating this index, four arbitrary tonnage ranges were selected for each species. Tonnage ranges for each species were selected to cover the entire range of observed tonnages that may occur in any one block area. The midpoint tonnage of each range was divided by 100 for the northern anchovy and by 10 for Pacific bonito, jack mackerel, Pacific mackerel, and Pacific sardine to provide a tonnage range value (X) of convenient size to be used in the

TABLE 4.—Day/night differences in tonnage and ratios observed based on average tons observed per block area flight in each zone for the period September 1962-1966.

Species and zone	Tons/block area flight day/night	Day/night ratio
Northern anchovy		
Zone A	478.8/636.1	0.75
B	148.5/832.2	0.17
C	45.4/386.4	0.11
D	32.6/337.5	0.09
E	9.8/214.0	0.04
F	3.9/ 39.2	0.01
G	105.0/197.3	0.53
H	64.4/ 75.8	0.84
I	10.8/ 92.3	0.11
J	32.6/237.1	0.13
K	13.5/ 11.1	1.21
Average—all zones	79.8/299.7	0.26
Pacific bonito		
Zone A	0.6/ 0.0	--
B	0.5/ 0.2	2.50
C	15.8/ 7.6	2.00
D	12.8/ 2.1	6.09
E	44.5/ 0.1	445.00
F	0.6/ 0.0	--
G	5.8/ 0.9	6.44
H	5.5/ 2.2	2.50
I	7.0/ 0.8	8.75
J	27.6/ 11.3	2.44
K	0.2/ 0.0	--
Average—all zones	10.9/ 2.3	4.73
Jack mackerel		
Zone A	41.7/ 12.2	3.48
B	25.3/ 44.8	0.56
C	2.5/ 6.0	0.41
D	9.2/ 34.6	0.27
E	2.5/ 19.2	0.13
F	8.0/169.4	0.04
G	2.3/ 6.1	0.37
H	1.7/ 8.2	0.20
I	5.8/ 17.0	0.34
J	4.0/ 11.5	0.34
K	0.0/ 0.0	--
Average—all zones	7.7/ 18.4	0.41
Pacific mackerel		
Zone A	0.0/ 0.0	--
B	0.0/ 1.1	0.00
C	0.8/ 5.7	0.14
D	2.5/ 3.8	0.65
E	0.5/ 6.4	0.07
F	50.1/ 50.3	0.99
G	2.0/ 2.0	1.00
H	11.1/ 5.9	1.88
I	1.7/ 2.4	0.70
J	2.7/ 8.4	0.32
K	3.2/ 0.0	--
Average—all zones	2.6/ 5.2	0.50
Pacific sardine		
Zone A	9.5/ 4.5	2.11
B	0.6/ 3.9	0.15
C	0.1/ 0.1	1.00
D	0.2/ 0.2	1.00
E	3.0/ 57.4	0.05
F	16.6/ 6.1	2.72
G	0.2/ 1.2	0.16
H	0.2/ 7.0	0.02
I	0.0/ 0.0	--
J	0.1/ 1.1	0.90
K	0.0/ 0.0	--
Average—all zones	0.7/ 4.1	0.17
Yellowtail		
(Note, small number of observations, zone data omitted.)		
Average—all zones	0.09/0.02	4.50
Pacific barracuda		
(Note, small number of observations, zone data omitted.)		
Average—all zones	0.06/0.29	0.20

TABLE 5.—Average weight per school (data from September 1962 through December 1966).

Species	Total tons No. schools obs.	=	Avg. tons/school
Northern anchovy	$\frac{192,047.5}{5,261}$	=	36.5
Pacific sardine	$\frac{5,140.5}{194}$	=	26.5
Jack mackerel	$\frac{44,545}{1,846}$	=	24.1
Skipjack tuna	$\frac{260}{14}$	=	18.6
Albacore	$\frac{73}{4}$	=	18.2
Bluefin tuna	$\frac{7,092}{396}$	=	17.9
Pacific bonito	$\frac{38,435}{2,244}$	=	17.1
Pacific mackerel	$\frac{10,948}{649}$	=	16.9
Yellowtail	$\frac{754.5}{53}$	=	14.2
White seabass	$\frac{234}{47}$	=	4.9
Pacific barracuda	$\frac{834.5}{184}$	=	4.5

index formula. Midpoints were not reduced for Pacific barracuda and yellowtail. Range of observed tonnage and X values are shown in Table 6.

The following formula was used to calculate annual indexes of apparent abundance, day and night, for each species by zone and the day/night index of annual average apparent abundance for each species.

Index of apparent abundance

$$= \frac{\sum N_i X_i + N_2 X_2 + N_3 X_3 + N_4 X_4}{N_t}$$

where: $N_{1,2,3,4}$ = number of block area flights in which the species occurred at value $X_{1,2,3,4}$.

$X_{1,2,3,4}$ = tonnage range values.

N_t = total number of block area flights in the zone during the year.

Day and night indexes of apparent abundance for each zone and the annual average day/night indexes of apparent abundance for all zones are listed in Table 7.

DISCUSSION AND SUMMARY

A direct, precise measure of total abundance is most desirable for the management of pelagic marine species. However, at the present time and into the foreseeable future, this degree of accuracy in the measurement of total abundance cannot be attained. Therefore, pelagic resource management will be required to rely on an indirect measure of total abundance. Some observations on the relation between the index of apparent abundance and changes in estimates of total abundance can be made. For the years 1963 through 1969, either separately or combined, some data are available giving estimates of total abundance, spawning biomass, or indexes of abundance for such species as the northern anchovy, Pacific mackerel, Pacific sardine, jack mackerel, and Pacific bonito. However, all such estimates were calculated from data obtained from such measures as catch, effort, catch composition, fecundity, and egg and larval counts. No direct measurements of total abundance were

TABLE 6.—Range of tonnage and tonnage range values (X).

Species	Observed tonnage	X
Anchovy	0-400	2
	400-1,000	7
	1,000-10,000	55
	10,000-20,000	150
Pacific bonito	0-50	2.5
	50-150	10
	150-1,000	57.5
	1,000-5,000	300
Jack mackerel	0-50	2.5
	50-300	17.5
	300-1,000	65.5
	1,000-2,000	150
Pacific mackerel	0-20	1
	20-100	6
	100-250	17.6
	250-500	37.5
Pacific sardine	0-100	5
	100-500	30
	500-2,000	125
	2,000-4,000	300
Pacific barracuda	0-10	5
	10-30	20
	30-80	55
	80-160	120
Yellowtail	0-5	2.5
	5-10	7.5
	10-30	20
	30-60	45

TABLE 7.—Annual average indexes of apparent abundance for both day and night observations. Dash (--) indicates no flight observations in zone. Indexes given as day/night.

Zone	1962	1963	1964	1965	1966	1967	1968	1969
Northern anchovy								
A	0.51/1.22	10.98/13.28	0.80/7.32	2.51/2.48	2.02/ 6.33	1.15/ --	0.28/ --	0.00/ 0.00
B	3.25/3.18	6.17/13.02	4.08/3.08	1.85/5.75	0.29/15.31	0.28/ 0.30	0.73/ --	0.03/ 0.00
C	0.05/0.99	0.40/ 2.70	0.90/2.85	1.82/8.63	0.27/ 2.79	2.91/ 3.03	0.05/ 1.76	0.87/ 1.93
D	0.00/2.97	1.24/10.02	0.23/4.75	0.48/3.67	0.14/ 6.73	0.63/ 5.12	0.05/ 3.24	0.41/ 1.96
E	--/0.00	0.00/ 1.05	0.00/3.14	0.00/0.12	1.09/ 0.23	3.15/ 0.11	0.18/ 0.12	0.32/ 0.67
F	--/0.00	3.66/ 1.71	5.75/0.37	0.00/0.58	0.00/ 2.61	0.00/ 0.00	0.00/ 0.60	0.00/ 0.00
G	--/1.00	0.51/ 1.81	0.54/6.21	1.42/3.23	2.24/ 1.78	2.40/ 8.32	0.55/ 2.11	5.01/ 8.57
H	--/--	0.14/ 0.12	0.38/1.00	0.05/1.90	2.28/ 1.43	5.45/ 1.60	0.65/ 0.58	6.35/ 3.26
I	--/--	0.14/ 0.00	0.05/0.11	0.02/0.34	0.28/ 2.53	2.87/ 0.71	0.18/ 0.21	0.78/ 0.49
J	--/--	0.78/ 0.67	0.85/6.08	0.00/0.00	0.45/ 1.55	0.16/20.16	0.52/ 1.11	0.55/ 3.39
K	--/--	0.00/ --	0.00/--	0.00/--	0.00/ 0.22	0.00/ 0.70	2.44/ 0.06	0.00/ 0.00
Average all zones	1.79/1.99	1.64/ 2.99	1.03/3.90	0.96/4.18	0.84/ 3.62	1.78/ 4.30	0.33/ 1.46	1.30/ 4.35
Pacific bonito								
A	0.00/0.00	0.00/ 0.00	0.50/0.00	0.00/0.00	0.04/ 0.00	0.07/ --	0.00/ --	0.00/ 0.00
B	0.01/0.00	0.00/ 0.01	0.06/0.01	0.02/0.00	0.43/ 0.00	0.01/ 0.00	0.00/ --	0.00/ 0.00
C	0.62/0.25	3.63/ 1.51	2.40/0.82	2.18/0.40	1.38/ 0.83	0.51/ 1.02	0.36/ 1.36	0.29/ 0.27
D	0.83/0.63	0.65/ 1.88	1.40/0.12	0.85/0.10	1.27/ 0.54	0.38/ 0.80	0.53/ 0.15	0.24/ 0.23
E	--/0.00	0.02/ 1.15	0.50/0.00	6.81/0.00	4.30/ 0.00	0.00/ 0.00	0.00/ 0.02	0.00/ 0.00
F	--/0.00	0.00/ 0.00	0.43/0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
G	--/0.00	0.31/ 0.37	0.30/0.00	0.50/0.01	1.19/ 0.16	0.67/ 0.39	0.12/ 0.13	0.12/ 0.16
H	--/--	0.85/ 0.22	2.12/0.53	2.06/0.32	0.03/ 0.00	0.00/ 0.02	0.68/ 0.24	0.09/ 0.06
I	--/--	0.00/ 0.45	3.46/0.54	0.40/0.13	0.06/ 0.02	0.12/ 0.00	0.02/ 0.03	0.02/ 0.05
J	--/--	3.67/ 0.23	1.10/0.06	1.71/0.46	4.96/ 0.11	3.27/ 0.12	1.70/ 0.69	0.64/ 0.51
K	--/--	0.13/ --	0.00/--	0.00/--	0.00/ 0.00	45.73/ 0.00	0.26/ 0.00	0.75/ 0.00
Average all zones	0.23/0.19	1.62/ 0.58	1.62/0.28	1.26/0.19	1.34/ 0.35	1.35/ 0.34	0.43/ 0.35	0.26/ 0.18
Jack mackerel								
A	0.00/0.08	1.81/ 0.00	8.32/2.89	0.78/ 1.67	4.29/25.72	0.81/ --	0.91/ --	0.03/ 0.00
B	0.02/0.00	3.48/ 1.37	6.65/6.67	1.03/ 1.22	0.74/ 8.78	0.78/ 1.34	0.70/ --	0.00/ 0.00
C	1.59/0.45	0.96/ 0.49	0.83/0.56	0.14/ 0.33	0.06/ 0.03	0.04/ 0.33	0.13/ 0.02	0.11/ 0.17
D	0.00/1.45	1.79/13.77	2.72/5.36	1.44/ 1.40	0.24/ 1.62	0.41/ 0.24	0.21/ 0.20	0.15/ 0.33
E	--/0.00	0.27/ 4.74	0.93/2.31	0.72/ 1.55	0.16/ 7.38	0.00/ 2.15	0.24/ 4.09	0.00/ 4.41
F	--/2.91	11.16/39.70	1.63/2.31	0.00/17.41	0.00/27.91	0.00/38.84	10.87/27.77	3.50/13.08
G	--/0.00	1.23/ 1.76	0.64/0.99	0.02/ 0.29	0.00/ 1.05	0.00/ 0.10	0.02/ 0.00	0.13/ 0.26
H	--/--	0.56/ 1.34	0.01/1.11	0.71/ 0.43	0.04/ 2.18	0.01/ 0.33	0.00/ 0.26	0.00/ 0.59
I	--/--	2.11/ 5.53	0.17/1.86	1.35/ 0.75	0.19/ 2.37	0.04/ 3.27	0.00/ 1.27	0.04/ 1.58
J	--/--	0.67/ 0.54	0.72/1.51	0.86/ 0.96	0.00/ 0.06	0.00/ 0.03	0.08/ 1.07	0.06/ 0.30
K	--/--	0.00/ --	0.00/--	0.00/ --	0.00/ 0.00	0.00/ 1.75	0.00/ 1.09	0.00/ 0.00
Average all zones	0.51/0.46	1.41/ 2.98	1.62/2.18	0.71/ 1.36	0.28/ 1.94	0.20/ 1.41	0.30/ 2.25	0.11/ 0.65
Pacific mackerel								
A	0.00/ 0.00	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ --	0.00/ --	0.00/ 0.00
B	0.30/ 0.03	0.00/ 1.56	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ --	0.00/ 0.00
C	0.00/ 3.15	0.23/ 0.37	0.03/0.30	0.04/ 0.28	0.01/ 0.35	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
D	0.50/ 0.30	1.41/ 2.20	0.49/0.23	0.05/ 0.08	0.00/ 0.01	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
E	--/ 3.75	0.43/ 0.67	0.02/0.74	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.03	0.00/ 0.00
F	--/ 0.00	5.40/ 6.59	3.15/3.62	0.00/ 0.23	0.00/ 2.95	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
G	--/18.75	0.79/ 0.46	0.78/0.13	0.00/ 0.44	0.00/ 0.04	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
H	--/ --	2.19/ 1.62	0.14/0.36	0.00/ 0.02	0.00/ 0.02	0.00/ 0.00	0.00/ 0.00	0.00/ 0.03
I	--/ --	0.76/ 0.40	0.01/0.53	0.00/ 0.11	0.00/ 0.09	0.00/ 0.02	0.00/ 0.00	0.00/ 0.04
J	--/ --	0.83/ 1.44	0.75/0.29	0.00/ 0.36	0.00/ 0.06	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
K	--/ --	1.94/ --	0.00/--	0.00/ --	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
Average all zones	0.17/ 1.26	0.79/ 0.91	0.33/0.33	0.01/ 0.19	0.00/ 0.14	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00

TABLE 7.—Continued.

Zone	1962	1963	1964	1965	1966	1967	1968	1969
Pacific sardine								
A	0.00/ 0.00	1.40/ 3.78	1.22/0.05	0.04/ 0.00	0.00/ 0.00	0.00/ --	0.00/ --	0.00/ 0.00
B	0.05/ 2.13	0.31/ 0.00	0.26/1.63	0.00/ 0.00	0.00/ 0.38	0.00/ 0.00	0.00/ --	0.00/ 0.00
C	0.04/ 0.00	0.02/ 0.00	0.00/0.05	0.07/ 0.02	0.00/ 0.00	0.00/ 0.03	0.00/ 0.00	0.00/ 0.00
D	0.00/ 0.28	0.07/ 2.36	0.23/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
E	--/12.50	2.22/ 0.83	1.75/7.87	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
F	--/ 0.00	0.00/ 0.00	13.47/1.62	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
G	--/ 0.00	0.08/ 0.30	0.17/0.13	0.03/ 0.00	0.00/ 0.09	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
H	--/ --	0.06/ 0.67	0.00/2.27	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.02	0.00/ 0.00
I	--/ --	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.02	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
J	--/ --	0.12/ 0.05	0.22/0.01	0.00/ 1.09	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
K	--/ --	0.00/ --	0.00/ --	0.00/ --	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
Average all zones	0.04/ 1.00	0.22/ 0.50	0.27/1.03	0.02/ 0.05	0.00/ 0.04	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
Pacific barracuda								
A	0.00/ 0.00	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ --	0.00/ --	0.00/ 0.00
B	0.00/ 0.00	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.24/ 0.00	0.00/ 0.00	0.00/ --	0.00/ 0.00
C	0.00/ 0.00	0.34/ 0.43	0.45/0.48	0.25/ 0.00	0.02/ 0.00	0.02/ 0.00	0.03/ 0.01	0.04/ 0.00
D	0.00/ 0.00	0.00/ 0.00	0.00/0.01	0.00/ 0.00	0.01/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
E	--/ 0.00	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
F	--/ 0.00	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
G	--/ 0.00	0.00/ 0.11	0.00/0.00	0.02/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
H	--/ --	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.11/ 0.00	0.00/ 0.00	0.00/ 0.00
I	--/ --	0.00/ 0.00	0.00/0.31	0.40/ 0.00	0.02/ 0.00	0.01/ 0.00	0.00/ 0.00	0.00/ 0.00
J	--/ --	0.15/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.04/ 0.00
K	--/ --	0.04/ --	0.00/ --	0.00/ --	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
Average all zones	0.00/ 0.00	0.08/ 0.15	0.08/0.12	0.10/ 0.00	0.03/ 0.00	0.00/ 0.00	0.01/ 0.00	0.02/ 0.00
Yellowtail								
A	0.00/ 0.00	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ --	0.00/ --	0.00/ 0.00
B	0.00/ 0.00	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.07/ 0.00	0.00/ 0.00	0.00/ --	0.00/ 0.00
C	0.00/ 0.00	0.03/ 0.04	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
D	0.00/ 0.00	0.36/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
E	--/ 0.00	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
F	--/ 0.00	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
G	--/ 0.00	0.00/ 0.00	0.00/0.00	0.01/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
H	--/ --	0.00/ 0.00	0.00/0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
I	--/ --	0.55/ 0.64	0.13/0.04	0.34/ 0.07	0.39/ 0.00	0.09/ 0.00	0.00/ 0.00	0.00/ 0.00
J	--/ --	0.63/ 0.10	0.00/0.00	0.16/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
K	--/ --	0.00/ --	0.00/ --	0.00/ --	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
Average all zones	0.00/ 0.00	0.19/ 0.06	0.01/0.00	0.06/ 0.00	0.04/ 0.00	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00

made which would provide a precise count of the population size.

From data for 1962 through 1966 the diurnal/nocturnal ratios in tonnage observed and in sightings indicate that the northern anchovy, jack mackerel, Pacific mackerel, and Pacific sardine were observed more frequently and in greater quantities at night. Pacific bonito and yellowtail were observed more frequently and in greater quantities during the day. However, Pacific barracuda were observed in greater quantity at night but more frequently during the day.

Indexes of apparent abundance for day and night observations and variations in total com-

mercial catch (Lyles, 1963, 1964, 1965, 1966; Keilman and Allan, 1969) during the years 1963 through 1969 are shown in Figures 4 through 7. The records for 1962 were incomplete (program initiated in September 1962) and were not considered in the discussion of the index.

In consideration of the day/night ratios, the indexes reflect the following:

Pacific sardine (Figure 4)—The Pacific sardine is observed in greater quantity and more frequently during the night; therefore, the night index should provide a better measure of the sardine's apparent abundance. The night index declined from 0.50 in 1963 to an index of less

than 0.00 in 1969. Some positive index values of less than 0.005 will be recorded as 0.00.

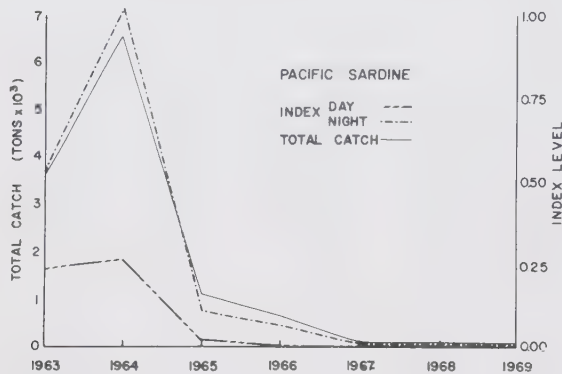


FIGURE 4.—Total catch and average index value for the Pacific sardine.

Pacific mackerel (Figure 5)—Data show that Pacific mackerel are observed in greater frequency and abundance during the night; therefore, the night index should be a better indicator of apparent abundance. The night index declined sharply from 0.91 in 1963 to 0.14 in 1966 and continued the decline to less than 0.00 in 1969.

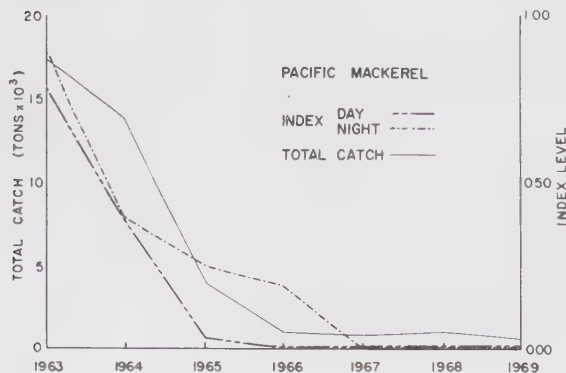


FIGURE 5.—Total catch, average index values for the Pacific mackerel.

Jack mackerel (Figure 6)—Observation of data show that jack mackerel is sighted more frequently and in greater abundance during the

night; therefore, the night index should be the best measure of apparent abundance. The night index declined from 2.98 in 1963 to 1.36 in 1965; however, the index level showed an increase in 1968 to 2.25 and a sharp decline in 1969 to 0.65.

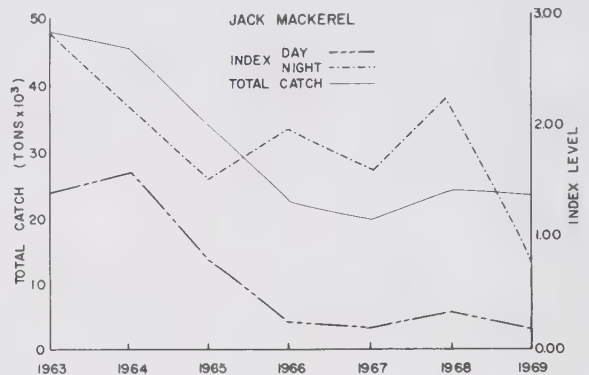


FIGURE 6.—Total catch and average index values for the jack mackerel.

Pacific bonito (Figure 7)—Bonito are observed in greater frequency and abundance during the day; therefore, the day index better represents any changes in apparent abundance. The day index showed only a slight decline during the 1963-1967 period, declining from 1.62 to 1.34. However, since 1967 the index has declined rapidly to a low in 1969 of 0.18.

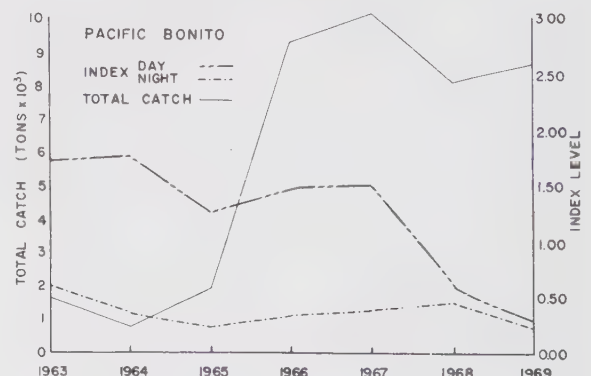


FIGURE 7.—Total catch and average index values for the Pacific bonito.

Northern anchovy (Figure 8)—Data indicate that the northern anchovy is observed more frequently and in abundance during the night; therefore, the night index should better reflect the apparent abundance of this species. The night index increased from 2.99 in 1963 to 4.30 in 1967, declined in 1968 to 1.46, and increased to a high level of 4.35 in 1969.

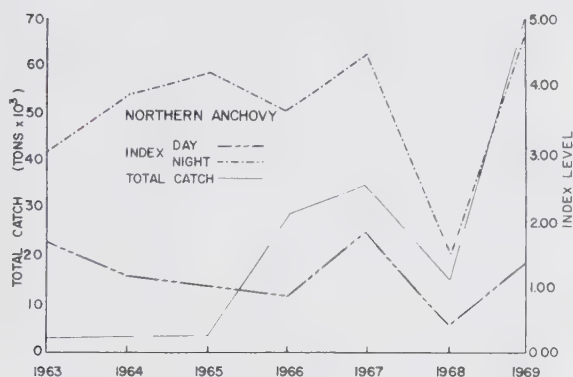


FIGURE 8.—Total catch and average index values for the northern anchovy.

Yellowtail and barracuda—Indexes have declined for both species (see Table 7); however, the frequency of observation was low, and no comparisons can be made with trends in abundance.

The relation between the trend of the apparent abundance index and of the trend of abundance estimates, where available, are discussed for the following species:

Pacific sardine—During the period 1963-1969, the Pacific sardine population continued to decline to a very low level, and the population is now at a fraction of that calculated for the 1930's and 1940's. Since no recent annual estimates are available (latest is 190,000 tons for 1959), a direct comparison of the estimates of total abundance with the index of apparent abundance cannot be made; however, the trend of the index follows closely the downward trend of the commercial catch.

Pacific mackerel—The Pacific mackerel fishery in southern California has been the subject of comprehensive research by the California De-

partment of Fish and Game for many years. For purposes of comparison between trends of the index and population estimates, the more recent data for Pacific mackerel provides the best source of comparative statistics.

The Pacific mackerel catch has declined to a low level in recent years, and the trend of the index follows closely the catch decline (see Figure 5). Population estimates have been calculated by a number of workers. Blunt and Parrish (1969) summarized the knowledge of this fishery and reported estimates of total spawning biomass of 160 million pounds in 1963. Blunt³ (personal communication) computed revised estimates for California waters using a modification of the Murphy method (Murphy, 1966). Revised figures indicate a spawning biomass of 64.5 thousand tons in 1962 and 78.5 thousand tons in 1963 reducing to less than 5,000 tons in 1968, an 84% or more, decline from 1963. The night index follows this 84% decline in estimated spawning biomass with an 89% index decline from 1.26 in 1963 to 0.14 in 1966 and to less than 0.00 in 1968.

Jack mackerel—Jack mackerel total abundance estimates are derived from egg and larval surveys. Ahlstrom (1968) estimated the adult spawning population in 1951-1954 for the California area to be between 1.4 and 2.4 million tons and that the resource was "much to moderately underutilized." In 1968 he estimated the population level to be approximately the same as was found in the earlier years.

The commercial fishery has experienced a substantial decline in catch over the past years and has extended its fishing grounds further offshore. Ahlstrom (1968) indicated the spawning population is centered in the oceanic waters. Blunt (1969) reported that in this offshore area the population is comprised of mature adults, some reaching the age of 30 years. The young fish remain inshore until 3 to 6 years old and then inhabit the offshore waters where they are outside the range of the normal fishery. The night aerial index shows a decline in apparent abun-

³ C. E. Blunt, Jr., California Department of Fish and Game, Marine Resources Branch, 1416 Ninth St., Sacramento, CA 95814.

dance of these inshore younger fish, and this decline follows the downward catch trend.

Pacific bonito—The Pacific bonito has been abundant in southern California waters since the advent of the "warm years" of 1957-1958. Its northward latitudinal range into southern California waters is influenced by environmental conditions (Radovich, 1963). Figures on total abundance are not available. However, an index of abundance off southern California was developed from party boat catches by Radovich (1963). It is believed that party boat catches reflect the bonito's general abundance off southern California within certain limits. These limits were not defined and are due to the anglers preference for fishing more desirable species such as barracuda, yellowtail, albacore, etc., when they are available rather than fishing for bonito. Blunt (personal communication; see footnote 3) continued Radovich's study and calculated an index based on catch per angler day for the years 1962 through 1968. Values are as follows: 1962, (1.7), 1963 (1.5), 1964 (2.4), 1965 (1.4), 1966 (0.9), 1967 (0.6), 1968 (1.4). The highest party boat index level was in 1964. The index shows an increase for 1968 and differs from the index of apparent abundance; however, this index has shown an overall decrease since 1964.

The day index of apparent abundance shows an overall decrease from 1963 through 1969. The Pacific bonito is classed as "much underutilized" by Ahlstrom (1968). Due to economic factors and a decline in catches of jack and Pacific mackerel, the catch of bonito increased sharply in 1966 and 1967 with only a slight reduction in catch during 1968 and 1969. In contrast to this increase in catch level, the index of apparent abundance has shown a substantial decrease from 1.26 in 1965 to 0.26 in 1969. A considerable reduction in catch was experienced in 1970 (Lester A. Keilman, personal communication) as the total catch declined to 4,600 tons, about one-half the 1969 catch.

Northern anchovy—Studies by Ahlstrom (1968) estimated a total population of 1.8 to 2.3 million tons in 1958, increasing to 4.5 to 5.6 million tons in 1968. This estimate was based on data from larval counts and shows a population increase of approximately 8.6 times during the

period 1951 through 1968. No total population estimates for the successive years 1963 through 1969 are available; however, Ahlstrom does state that the larval counts show that the population is somewhat variable from year to year and that the population reached a plateau in about 1962. Since annual abundance estimates are not available for the years 1963 through 1969, a direct comparison with the aerial spotter index cannot be made. The northern anchovy has increased substantially in abundance during the past decade and is classed as an underutilized species (Ahlstrom, 1968). Since it has been subjected only to minor fishery, except in 1969, it is generally agreed that the population level continued to be at high level throughout the years 1963-1969. The trend of the night aerial index of apparent abundance shows an overall increase during the years 1963 through 1969. The only significant change in apparent abundance was in 1968 when the index declined sharply; however, in 1969 it again increased to a high level.

Wide fluctuations in anchovy relative abundance were noted by Wood (1964, see footnote 2) during aerial surveys from 1956 to 1963. Future observations will determine if this paralleling of catch and apparent abundance will continue. Since the survey area covers an area common to the anchovy, trends in the annual index should be of use in evaluating catch variations and reflect the trend of total abundance in this underutilized resource.

In summary, for the geographical area normally surveyed by the aerial fish spotter, the author believes these data represent a reasonable index of apparent abundance. Like all other measures presently available, the true relation of the index of apparent abundance to total abundance for each species cannot be determined. However, from all data available concerning the Pacific mackerel, a species for which considerable and more reliable data on the adult population are available, the trend of the index follows the downward trend of the total abundance estimate. The index shows little effect from fluctuations in economic demand, as shown in data for the Pacific bonito. Trends in the abundance level of the Pacific bonito within the survey area are evident before they are reflected

in catches, and it appears to be a useful index in the evaluation of catch variations and long-term trends in total abundance in underutilized pelagic surface schooling resources.

ACKNOWLEDGMENTS

The author wishes to acknowledge the cooperation and interest of aerial fish spotter pilots who participated in the program from 1962 through 1969; Edward Durden, Leon Durden, Jack Mardesich, Paul Mardesich, Joseph Miles, John Bourgois, Jack Whalen, John O'Conner, Rodger Hillhouse, and Tony Marinkovich.

The studies of Dr. Oscar E. Sette in the late 1940's must be recognized as one of the earliest applications of scientific aerial fish observations in the continuing search for new methods and techniques for obtaining abundance estimates of pelagic fishery resources.

Reynold A. Fredin of the National Marine Fisheries Service, Northwest Fisheries Center, Seattle, Wash., gave valuable assistance through suggestions on statistical processing methods for the aerial spotter data, as did Norman Abramson⁴ of the California Department of Fish and Game, Marine Resource Laboratory, Long Beach, Calif. The processing of the data by the Statistical Section of the California Department of Fish and Game, Marine Resources Laboratory under the direction of Edward Greenwood was appreciated, as were suggestions of the staff of the Statistical Section on original coding of the data.

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Review of Recent Progress in Coastal Aquaculture in the United States

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Abstract

The progress in coastal aquaculture in the United States during the last two years is reviewed in detail. Among the fin-fish and shell-fish cultivated commercially, *Crassostrea virginica* and *C. gigas* are the most important, the latter particularly on the Pacific Coast. There are about 74 870 ha of leased oyster beds and about 1.6 million ha of public oyster grounds, with potential for considerable expansion.

One of the important species of prawn suitable for culture is *Macrobrachium rosenbergii*, experiments on which have been in progress in Hawaii. It has been estimated that production up to 2.2 t/ha/year of this prawn is feasible. Interest in research on rearing several marine species of shrimps continues to grow in the U.S., the important species being *Penaeus duorarum*, *P. aztecus* and *P. setiferus*. Other invertebrates receiving increased attention are *Panulirus argus*, *Homarus americanus*, *Mercenaria mercenaria* and *Mya arenaria*.

The Florida pompano, *Trachinotus carolinus*, has been the object of intense research in the U.S. The important critical problems to be solved for pond production of the fish are temperature control, providing a suitable diet, artificial spawning and rearing of larvae and control of parasites. The other species of fish receiving increased attention in this respect are also mentioned.

1 INTRODUCTION

In a paper to the 13th Session of the Indo-Pacific Fisheries Council, Brisbane, Australia, October 1968, Higgins and Nakamura (1968) defined coastal aquaculture and reviewed the species cultivated, potentially important species, productivity of oysters, and technical and economic problems associated with coastal aquaculture in the United States. The definition of Higgins and Nakamura is adhered to in this report, which reviews the progress that has taken place in coastal aquaculture in the past two years. With the exception of the oyster, coastal aquaculture of marine fin-fish and shell-fish has not been developed for a sufficiently long period, so that data on area and scope of production, manpower, yield, productivity, source of seeds and other information on management and cost factors are either not available or at best preliminary. Therefore, although some factual information on oyster culture and production is presented in this

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account the remaining sections on shrimps, other invertebrates and fish are restricted to reviews of some of the experiments and problems associated with attempts to culture them in the United States. For further details on coastal aquaculture in the United States the works of Iversen (1968), Ryther (1968), Ryther and Bardach (1968) and Bardach (1968b) may be consulted.

2 OYSTERS

Among the species of fin-fish and shell-fish cultivated commercially in the United States, the American oyster, *Crassostrea virginica*, is by far the most important. The Pacific oyster, *Crassostrea gigas*, is another species of considerable importance, particularly along the Pacific Coast.

2.1 Area and scope

According to Ryther (1968), there are about 185 000 acres (74 870 ha) of leased oyster beds and about 4 million acres (1.6 million ha) of public oyster grounds in the United States. The potential exists for a very considerable expansion of oyster culture. Estimates say that around Long Island, New York, there are at least 9 million acres (3.6 million ha) of approved shell-fish producing grounds, but only 40 000 acres (16 190 ha) are currently available for lease. However, only a small fraction of the available lease properties is actively farmed. On the Pacific Coast, Washington, which produces over 80 per cent of the Pacific oyster, has large areas of tidal flats suitable for oyster culture (Iversen, 1968), and suitable grounds are also available in California.

2.2 Manpower

It is difficult to obtain accurate estimates of the manpower presently engaged in oyster culture, because of the many small hatcheries and farms. Ryther (1968), in describing the operation of a hatchery on Long Island Sound, stated that it required a trained professional staff of 2-4 people and an additional 5-10 workers during peak activity. This commercial hatchery currently leases about 2 600 acres (1 050 ha) of oyster beds in waters with a mean depth of 2-35 ft (0.9-10.7 m).

2.3 Yield and productivity

Webber and Riordan (1969) have pointed out that in the U.S.A., public grounds are unmanaged and the yield is poor but private oyster farms, where oysters are moved from setting grounds to growing grounds and predators are controlled, produced on average nearly 20 times as much

I. Regional and Country Reports

as the unmanaged grounds. In comparing total production between leased and public grounds, Ryther (1968) noted that some 15 430 short tons (14 000 metric tons) of oyster meat are produced from 185 000 acres (74 870 ha) of leased or privately owned beds, the same amount as that produced on about 4 million acres (1.6 million ha) of public oyster grounds. Bardach (1968a) reported that cultivation of stocked or natural populations of oysters on public grounds yielded an average of 8 lb/acre/year (9 kg/ha/year), whereas stocked populations on leased grounds under intensive cultivation produced 4 460 lb/acre/year (5 000 kg/ha/year).

2.4 Source of seed

Ryther (1968) noted that natural seed oyster production in the northeastern United States is presently very restricted and undependable because of pollution, dredging and filling, which change the ecology of the oyster's natural environment. To alleviate the shortage, farmers have attempted to raise seed oysters imported from the Central and South Atlantic States, but had little success because the oysters, although of the same species, apparently could not adapt to the environmental conditions of the north. The result is that, at present, four commercial hatcheries are producing seed oysters for the farmers of the northeastern states.

In the Pacific Northwest, attempts to establish spawning stocks of the Pacific oyster, *C. gigas*, have been unsuccessful, although the oysters grow very well in the tidal flats along the coast of Washington (Iversen, 1968). Spawning has been reported to be successful on a few occasions in some areas, but the supply of seed oysters is highly irregular. As a result, the culture of Pacific oysters, which may reach 8 million pounds (3 600 metric tons) annually, is based almost entirely on seed oysters imported from Japan.

In those states bordering the Gulf of Mexico, the spat of the American oyster are collected by setting out oyster shells in oyster spawning areas (Iversen, 1968).

2.5 Culture management

The operations of oyster hatcheries, as we know them today, are briefly described below (Ryther, 1968; Davis, 1969). In commercial hatcheries, oysters are spawned under controlled conditions. Sexually mature adult oysters, selected from the growing beds, are held in the hatchery at 10°C (50°F), then conditioned for spawning by slowly raising the temperature and holding the oysters at 18°C (64.4°F) for 2-4 weeks. When the temperature is raised to 25°C (77°F), the oysters begin

spawning. It has been estimated that a single female may release 70 million eggs at one spawning.

Fertilized eggs are transferred to rearing vats until development to the straight-hinge stage; the larvae then undergo screening until only the larger, rapidly growing individuals, representing roughly 20 per cent of the total production, remain. Transferred to tanks holding specially prepared water of natural or inoculated algal culture and fertilizer, the larvae start to feed on the algae. If the culture is not sufficiently dense to supply the needs of the oyster larvae, supplemental direct feeding of algal culture is required. Species used for the feeding are flagellates *Isochrysis galbana*, *Monochrysis lutheri*, and *Rhodomonas* sp., and experience has shown that a mixture of at least two different species is required. The rate of feeding of algal culture is about 2 000 cells/larvae/day.

When the larvae are ready to set, usually in about 10-15 days, they are transferred to plastic tanks which contain a layer of specially selected, screened and washed oyster shells. The larvae attach to the shells as they metamorphose. The cultch with spats attached, is then placed in polyethylene net bags hung on racks, and immersed in post-setting tanks. The larvae are fed water containing algal bloom; high temperatures and supplemental feeding result in rapid growth of the young seed oysters. After a few days, the seed oysters are about 0.06-0.12 inch (1.5-3.0 mm) in diameter. Only then are the racks with shell bags attached, transferred outside to the dock, where they are placed on a floating raft. Seed oysters are kept in open waters for about 2-3 additional weeks until they reach a size of about 0.25-0.50 inch (6.3-12.7 mm). The entire hatchery operation from spawning to fingernail-size seed oyster requires 4-6 weeks. Because of the seasonal variation in the water temperature hatchery operations are restricted to late spring and summer.

Year-round hatchery production for seed oysters is a distinct possibility (Ryther, 1968). At Long Island, water used by a local power company to cool its machinery is discharged into a 7-acre (2.8-ha) lagoon. The discharged water being 7°-10° C (12.6°-18° F) warmer than the intake water, is very beneficial for clam and oyster growth. Preliminary tests have shown that oysters and hard clams can not only survive, but also grow exceptionally fast in the cooling water. This cooling water is nontoxic and has a high nutrient content to support a luxuriant growth of microscopic algae. The lagoon may prove to be better for year-round seed oyster production after all the tests are completed. High midsummer temperatures, reaching 30°-32° C (86°-89.6° F) proved beneficial as the seed oyster showed exceptionally rapid growth, contrary to the belief that the high temperatures would arrest growth and might even be lethal.

1. Regional and Country Reports

The rate at which seed oysters are planted on commercial beds is about 500 bushels/acre (43.5 kl/ha) (Ryther, 1968). After 1 year on the bottom, the seed oysters have increased in size to 5 000 bushels (176.2 kl) and redistributed on 5 acres (2 ha) of oyster beds. By 3 years, the density is about 10 000 bushels (352.4 kl) and again the oysters require redistribution on 10 acres (4 ha) of bottom. Projections at this rate of planting indicate that 500 bushels of seed oysters/acre (43.5 kl/ha) could reach 500 bushels of marketable oysters/acre.

Not all the Atlantic Coast oyster farmers require hatchery produced seed oysters. Along the gulf and south to mid-Atlantic coasts, the oyster farmers have no difficulty in obtaining a successful set of seed oysters: the adults, however, are susceptible to widespread infection and mortality (Ryther, 1968). In the Hawaiian Islands, private fishpond owners buy seed and adult oysters which have been removed from the oyster beds in West Loch, Pearl Harbour, Hawaii.

2.6 Cost-benefit factors

Cost-benefit data are not readily available for the United States oyster-culture industry, but a typical hatchery operation used as an example by Ryther (1968) should provide some idea of the capital investment required. For a commercial hatchery operation leasing about 2 600 acres (1 050 ha) of oyster beds, the capital investment required would be about \$100 000-\$200 000.

Under controlled conditions, the income from a privately leased oyster ground could be substantial. With the current wholesale prices of oysters at \$18/bushel (\$0.51/litre), a production of 500 bushels/acre/year (43.5 kl/ha/year) would generate a gross income of \$9 000/acre (\$22 240/ha). Estimates place the production of oysters from leased grounds in the United States at an average of about 0.66 short ton/acre/year (1.48 metric tons/ha/year), whereas the public grounds produce only 0.03 short ton/acre/year (0.07 ton/ha/year). These national averages, when compared to the projected production from a private operation, represent only about 1/30 and 1/600 of the projected yield. The difference is very striking. Ryther and Bardach (1968) pointed out that populations of oysters on public grounds yielded an average of 7.9 lb/acre/year (9 kg/ha/year) worth \$15/acre (\$38/ha), whereas the best yield on leased grounds under intensive cultivation reached 4 460 lb/acre/year (5 000 kg/ha/year) worth \$8 498/acre (\$21 000/ha).

2.7 Problems

Much of the research in oyster culture now being done in the United States revolves around the merits of new culture methods. Loss of

Recent Progress in Coastal Aquaculture in the United States

oyster grounds suitable for culturing, shortage of oysters in many areas, the increased value of oysters and commercial interest in seed oyster production have stimulated research into culture techniques (Shaw, 1969). In the past decade, the major interest has centred on the merits of bottom culture as now practised and off-bottom culture from rafts, platforms, trays, or other methods used in other countries.

The Maine Department of Sea and Shore Fisheries has experimented with strings of scallop shells suspended from rafts as spat collectors (Shaw, 1969). Shaw also reported that investigation of off-bottom oyster culture in Oyster Pond River, Chatham, Massachusetts has shown excellent growth of oysters that settled on scallop and oyster shells strung on wires and suspended from a log raft. In one experiment, 70 per cent of the oysters suspended for 1.5 years and then planted on the bottom for another year were marketable, whereas wild oysters grown on the bottom required 4-5 years to attain the same size. In reporting the research results from other states, Shaw (1969) noted that at Fishers Island, New York, 55 000 strings of scallop shells were suspended from 130 rafts in a 20-acre (8-ha) salt pond, and estimated production reached 25 million seed oysters annually; at Oxford, Maryland, where extensive studies on off-bottom cultures have been conducted since 1960, the results have shown that when suspended shells became fouled before the oyster larvae were ready to attach, they failed to catch a good set. Other significant findings were that oysters near the surface grew faster; that many oysters on the bottom portion of the strings were dead, and that oysters on strings held horizontally grew faster than those held vertically.

Investigations in North Carolina also proved of interest to oyster culturists (Shaw, 1969). Among the findings were, that asbestos plates were superior to plastic plates as spat collectors and that growth and number of oysters were best on plates measuring 8.25 x 8.25 inches (21.0 x 21.0 cm). Other results also showed that vertical spacing of 6-10 inches (15.2-25.4 cm) was superior to spacing of 2-4 inches (5.1-10.2 cm) and that strings that were aired 4 hr/day had greater survival and growth of oysters.

On the Pacific Coast in California, off-bottom culture of oysters is practised commercially on a small scale, the major centre for commercial off-bottom culture being Humboldt Bay (Shaw, 1969). Oysters farmed off the bottom in the bay reach marketable size in 18-24 months whereas those reared on the bottom require an additional 1-2 years to reach market size.

In Washington, seed oysters of *C. gigas* are caught commercially off-bottom in Dabob Bay. Settings of commercial levels were obtained for 10 out of 14 years. Results of tests have shown that setting is greater on rack-hung strings than on those hung from floats (Sayce and

I. Regional and Country Reports

Tufts, 1968). Small-scale, pilot-farm studies on Pacific oysters, *C. gigas*, and clams by fishery scientists at the University of Washington have shown that unspaced oyster shells treated with Sevin (an insecticide) collected more oyster larvae than the other cultch materials such as egg crate fillers coated with cement or with a cement-Sevin mixture, and plain untreated oyster shells (Chew, Nosh, and Lipovsky, 1970). The experiments were designed to study the possibility that low levels of insecticide toxicity function as an attraction to oyster larvae.

Experiments in Hawaiian fishponds have shown that seed oysters grow best when cultured in the surface layers of water (Hawaii, 1970). Seed oysters, obtained from the oyster beds in Pearl Harbour and transferred to fishponds, reached commercial size of 3 inches (7.6 cm) in a year's time when reared in trays.

Off-bottom culture of oysters in the United States is still beset with problems (Shaw, 1969). Many areas where off-bottom culture can be carried on are presently being used for recreation and navigation. Methods to control mortalities caused by fish, crabs and worms must also be developed, and fouling of the suspended shells by barnacles, bryozoans, and tunicates must be studied. In addition to predator- and disease-caused mortalities, Ryther and Bardach (1968) pointed out that the effects of man-made changes in the environment, the use of primitive methods and poor management practices are other problem areas that require study. Davis (1969) reported that only recently have genetic studies been initiated with the intent of producing new races of oysters that are fast growing, disease resistant, high in meat content, and tolerant to a wider range of physical factors.

Ryther (1968) believes that the prospects of large-scale raft or platform culture of oysters in the crowded waters of Long Island Sound are rather remote because of the heavy demand of this area for recreational use. Other major problems appear to be the irregular shape of the shell and heavy fouling, both of which make off-bottom cultured oysters unsuitable for the half-shell market. He suggests that perhaps a combination of two methods—off-bottom culture in private ponds during the first year to reduce mortalities from predation and silting and to obtain rapid growth, and bottom culture for shaping and final growth to market size—may prove to be a satisfactory solution.

In recent years, there has been a spectacular tenfold increase in oyster production from Long Island Sound, off Connecticut, and the factors responsible for this increase, according to MacKenzie (1970), were the efforts by government and industry scientists to develop better oyster-setting beds and new methods to control the major causes of mortality, and produce seed oysters under controlled conditions at the hatcheries. The use of improved equipment and scuba diving gear to

examine the oyster beds has also contributed significantly to better production.

Predation by starfish and oyster drill and silting are cited as some of the major causes of mortality on the oyster beds. It has been estimated that prior to 1966, starfish were responsible for mortality of 60-70 per cent of the young oysters, but by dragging cotton mops over the planted beds to determine the extent of starfish invasion and then applying quicklime at the rate of 1 600-2 000 lb/acre (1 793.4 - 2 241.7 kg/ha) to the infested areas, the oyster farmer can reduce starfish predation to only 5-10 per cent of the seed oysters (MacKenzie, 1970). In experiments to control predation by oyster drills, the National Marine Fisheries Service Biological Laboratory at Milford, Connecticut, used Polystream, a mixture of hydrocarbons, over the beds and was successful in destroying about 85 per cent of the drills. Seed-oyster mortality was reduced to about 2-5 per cent.

Silting causes suffocation among young oysters and although the average mortality rate from suffocation is about 20 per cent, it can be very serious with mortalities reaching upward to 75 per cent (MacKenzie, 1970). Silt accumulates up to 2 inches (5.1 cm) in winter covering the dormant oysters, but suffocation does not occur until the following spring when the oysters attempt to pump water as a result of an increase in their metabolic rate. Oyster companies have now learned to reduce silt mortalities by transplanting the oysters out of heavily silted areas earlier in the year.

The improved methods of controlling mortalities have been reflected in the increase in oyster production. Whereas oyster companies previously obtained 1 bushel (35.2 litres) of market oysters (200 oysters) from 1 bushel of seed oysters (5 000 seed oysters), nowadays the companies are obtaining yields of 10 or more bushels (352.4 litres) from 1 bushel of seed oysters (MacKenzie, 1970).

Other experiments on growth of oyster spats at the Milford Laboratory have shown that oyster spats have a better growth rate when reared in unfiltered, flowing sea water than recirculated water (FAO, 1970). When feeding was intensified, the spats showed no improvement in growth rate in recirculated water, but showed a growth rate 2-2.5 times greater in the unfiltered, flowing sea water.

3 SHRIMPS

The culture of shrimps, which has generated tremendous enthusiasm among mariculturists, offers the best possibilities for commercial culture among crustaceans. The insatiable market demand for shrimp in the United States and the high price paid for it have stimulated State

I. Regional and Country Reports

and Federal Government agencies and industry to develop methods for culturing shrimp.

One of the potentially important species of prawns mentioned by Higgins and Nakamura (1968) as being suitable for aquaculture, is *Macrobrachium rosenbergii*. Although the adults of this species are fresh-water forms, the larvae require brackish water for survival; therefore, it is discussed here as a species suitable for coastal aquaculture.

In the United States, the Hawaii Division of Fish and Game has taken the initiative in conducting experiments dealing with *M. rosenbergii* culture. In August 1964, the first lot of *M. rosenbergii*, consisting of four mature males and four gravid females, was imported into Hawaii through the cooperation of the Fisheries Division of Malaysia (Fujimura, 1966). Ten males and 18 females followed in additional lots. From this original breeding stock, the Division of Fish and Game produced and reared to maturity more than 3 000 second-generation prawns and by 1969 had produced an estimated 700 000 prawns (Hawaii, Department of Land and Natural Resources, 1970). Many of the details of rearing these prawns on a commercial scale were worked out at the same time. Briefly, the procedure is to place the newly hatched larvae in phytoplankton-rich "green" water which has a salinity of about 18 ppt (Fujimura, 1966). After 12 days, the larvae are transferred to clear water of the same salinity. In addition to their phytoplankton diet, the larvae feed on *Artemia salina* nauplii and ground fish flesh. The post-larval stage is reached in about 30 days; the juveniles are then farmed out to owners of fresh-water ponds for rearing to marketable adults. Having demonstrated that sufficient numbers of young prawns can be propagated to supply commercial prawn farmers, the Hawaii Division of Fish and Game is now concentrating on methods to reduce production costs from the present \$6.47/1 000 prawns to a more reasonable cost of about \$2.00/1 000.

Nine owners of private fresh-water ponds throughout the State of Hawaii have indicated interest in test-rearing young juvenile prawns to marketable size. The ponds, which vary in size from 0.25 to 6 acres (0.1 to 2.4 ha) and have a combined surface area of about 10 acres (4.0 ha) were stocked with a total of 207 000 juveniles. Faster growth rates have been achieved by supplemental feeding. Now marketing of prawns can be done after a little more than 1 year, whereas previously it required 2 years. Fujimura (1970) estimates that production of up to 1 ton/acre/year (2.4 metric tons/ha/year) is feasible.

Interest in research on rearing several marine species of shrimp continues to grow in the United States. Bardach (1968a) reported that the Biological Laboratory of the National Marine Fisheries Service in Galveston, Texas, the Bears Bluff Laboratory of the South Carolina

Recent Progress in Coastal Aquaculture in the United States

Wildlife Resources Commission and the Institute of Marine Sciences of the University of Miami in Florida are among the agencies that have taken the initiative in carrying out shrimp culture experiments. Broom (1969) reported that pond culture experiments of shrimp were started at Grand Terre Island, Louisiana, in 1962.

The culture of penaeid shrimps is still in the experimental stage in the southeastern United States. Idyll, Tabb, and Yang (1969) have noted that long-term research has started on the intensive culture of pink shrimp, *Penaeus duorarum*, with the support of the Armour Company, the United Fruit Company and the National Science Foundation under its "Sea Grant" programme. Facilities include four 0.25-acre (0.1-ha), two 0.5-acre (0.2-ha), and one 1-acre (0.4-ha) ponds. In addition, there will be 16 concrete outdoor larval rearing tanks, each with a capacity of 20 million tons (18.1 million metric tons). During the first year shrimps were successfully reared from egg to pond-stocking size. In Louisiana, Broom (1969) reported that brown shrimp, *Penaeus aztecus* and white shrimp, *P. setiferus*, were cultured experimentally in 0.25-acre (0.1-ha) ponds. Juveniles and postlarvae, obtained from several sources, were stocked at different rates and fed several types of feed. Tests showed that the best feeding rates were 5 and 10 per cent of their body weight at a stocking rate of 20 000/acre (49 400/ha). The annual production realized under this experimental condition ranged from 40 to 809 lb/acre (44.7-906.2 kg/ha) and food conversion ratios varied from 1.7 to 9.7. Other information obtained through the experimental culture operation showed that higher mortalities occurred in ponds stocked with postlarvae than in ponds stocked with juveniles; higher mortalities were also recorded in unfed ponds than in ponds receiving supplemental feed.

Using a method similar to that first described by Hudinaga [Fujinaga] of Japan for culturing larval shrimp, Cook and Murphy (1969) recently were successful in rearing relatively large numbers of penaeids in the laboratory. Slight modifications of this procedure have increased the yield of post-larval penaeid shrimp reared from eggs spawned in laboratory containers. Among the six species cultured were the commercially important brown, white and pink shrimps.

The method adopted by Cook and Murphy (1969) depends on wild stocks for the supply of females in spawning condition. Ripe penaeid shrimps, easily identified, are placed in 500- or 275-gallon (1 890- or 1 040-litre) round polyethylene tanks at the rate of one or two per tank. Only about one-third spawn viable eggs, usually during the first night after they are brought to the laboratory. After spawning, the adults are removed to prevent their eating the eggs, which hatch in 12-16 h. The emerging larvae do not feed during the naupliar stage; feeding begins at the protozoal stage. Among the algae used successfully

I. Regional and Country Reports

for feeding the protozoa are *Skeletonema costatum*, *Thalassiosira* sp., *Cyclotella nana*, *Phaeodactylum* sp., *Dunaliella* sp., *Gymnodinium splendens*, and *Exuviella* sp. During the mysis stage, they are fed newly hatched brine shrimp. From the results of the experiments, Cook and Murphy (1969) learned that temperature affected the rate of development throughout the larval stages. In water of 30 ppt salinity, brown shrimp reached the first larval stage in an average of 17 days at 24°C (75.2°F), 12.5 days at 28°C (82.4°F) and 11 days at 32°C (89.6°F). Highest survival of nauplii occurred at 24°C (75.2°F), and as the shrimp passed through the protozoa and mysis stages, survival usually increased with an increase in temperature. Salinities above 35 ppt or below 27 ppt were lethal to the larvae. Cook and Murphy (1969) found that food consisting of a mixture of *C. nana*, *Isochrysis galbana*, *S. costatum*, and *Thalassiosira* sp., or *Thalassiosira* sp. alone probably were the best. These investigators have just begun to study the physiological requirements and tolerances of larval shrimp, but they feel that the yield of postlarvae per volume of water should increase significantly as they learn more about the effects of temperature, salinity, and feeding rates on larval density.

Intensive research on shrimp culture is continuing in other parts of the United States. The Skidaway Institute of Oceanography in Savannah, Georgia, has become involved in experimental work on adapting the flowing water intensive culture techniques used in salmon and trout culture to the rearing of channel catfish, penaeid shrimps, and flounder (Andrews, 1970). One of the major objectives will be to develop a suitable pelleted shrimp diet using natural ingredients. Also related to nutrition will be research on protein, mineral, vitamin, lipid, carbohydrate, and amino acid requirements of the shrimp. Environmental and physiological experiments include studies on the effects of light, temperature, salinity, water input, water quality, and stocking rate on growth, efficiency of food conversion, and general health of the shrimp.

At the University of Washington, Price and Chew (1969) reported their success in artificially rearing large "spot" shrimp, *Pandalus platyceros* from egg to subadult stages. Using a closed recirculating salt water system, they determined that eggs collected from gravid females and incubated at 15°C (59°F) hatched earlier than at 11° and 13°C (51.8° and 55.4°F), but the larvae died shortly after hatching. Best survival of larvae was obtained at 11°C (51.8°F). The larval "spot" shrimp were fed *A. salina* nauplii; the post-larval stages were fed a supplementary diet of ground fish flesh, because the nauplii alone were found to be inadequate. Other studies by Price and Chew (1970) included the culture of *Pandalopsis dispar*. Eggs collected from dead, egg-bearing females caught in trawl tows were successfully hatched in specially designed containers. Detached eggs, hatching earlier than those

on the female, produced normal larvae; it was determined from the experiments that flow rates within the egg-hatching containers were more important than temperature in determining hatching time.

The fact that private industry has made tremendous progress toward the goal of culturing shrimps on a commercial scale can be seen in a recent report by Hull (1970). Marifarms, Inc., a commercial 2 500-acre (1 012-ha) shrimp farm in St. Andrews Bay, Panama City, Florida, is scheduling the first harvest of cultured shrimp in October 1970. Marifarms, employing about 60 people, concentrates its present efforts on producing shrimp for the food market and in the future hopes to become a supplier of post-larval shrimp to shrimp farmers. The procedure being used there at present is to collect gravid females of white, pink and brown shrimps in the wild and to induce spawning in captivity, although the farm is licensed to use the Japanese-developed Fujinaga process has the expertise necessary for raising and mating its own brood stock.

On reporting the culture method used at Marifarms Hull (1970) noted that after spawning, the young shrimp are nursed through several larval stages on specially cultured mixtures of phytoplankton, mainly diatoms. Survival of the young has averaged about 57-58 per cent, although a survival rate of 95 per cent was achieved in individual lots. After attaining a size of about < 0.1 oz (0.02 g) or 0.8 inch (20 mm) in about 3 weeks, the post-larvae are released into the nursery area.

Confined within the 2 500-acre (1 012-ha) main range is the 250-acre (101-ha) nursery area and in it the postlarvae undergo further growth; at the end of 3 months, they are released into the main range. From the time of hatching to harvesting requires about 7 months. The water of the main range is fertilized with a standard, commercial nitrate and phosphate fertilizer commonly used on lawns. Plankton and rooted grass flourish after fertilization and form the basis of the shrimp's diet; supplemental feeding includes ground-up trash fish.

Hull (1970) reported that the main range, prior to receiving the young shrimp, is cleared of predators by two methods: by encouraging the local fishermen to go into the range to harvest the fish and by using rotenone. Potassium permanganate is used outside the fenced range to neutralize excess rotenone; weekly antifouling patrols clear the nets along the entire seaward perimeter of other fouling organisms.

Managers of Marifarms have not determined the best way to harvest the shrimp (Hull, 1970). The yield is not expected to be large; a reasonable expectation is 300-500 lb/acre (336-560 kg/ha), but the first harvest is not expected to reach this level.¹ Hypothetically, if at a size

¹The first harvest in 1971 was reported to average 300 lb/acre (336 kg/ha).—Ed.

I. Regional and Country Reports

of 26-30 shrimps/lb a yield of 400 lb/acre (448 kg/ha) were feasible and could be sold for \$1.00/lb (\$2.20/kg), then a farm 2 500 acres (1 012 ha) in size could realize a gross income of \$ 1 000 000.

4 OTHER INVERTEBRATES

4.1 Spiny lobster

Another crustacean of high monetary value receiving increased interest as the object of mariculture is the spiny lobster, *Panulirus argus*. Provenzano (1969) has reviewed studies on larvae of the spiny lobster and the sand or slipper lobster (Scyllaridae) and has summarized results of importance to future studies.

In 1963, several attempts to rear phyllosoma larvae of a number of different species of lobster met with moderate success (Provenzano, 1969). Most effort was concentrated on phyllosomas of various sand lobsters because of their availability at that time. Studies on larvae of spiny lobster, carried on in conjunction with those of sand lobster larvae, showed that at temperatures above 20°C (68°F) spiny lobster larvae passed through as many as eight or nine moults and that some lived as long as 9 or 10 weeks. Growth was markedly slower after the first few moults, however, and, after 2 months, the larvae were much less developed than those found in their natural environment.

A major obstacle to rearing the phyllosoma larvae of spiny lobster to metamorphosis has been the providing of adequate food, particularly to the later-stage larvae. Brine shrimp, *A. salina* used extensively for feeding the larvae, did not satisfy the nutritional requirements of the later-stage larvae.

Taking a radically different approach to the problem of culturing spiny lobster, Ingle and Witham (1969) suggested that culturing should start after metamorphosis. Their studies have shown that at about the time of metamorphosis, the puerulus or first-stage postlarva migrates into shallow-water sanctuaries of coastal bays and lagoons. They also reported that phyllosomas are rarely found in plankton samples collected in bays and lagoons; the first and later stages, however, are readily found in these areas. Artificial habitats similar to those in which the postlarvae of spiny lobster are found were developed and although some of them did not attract any postlarvae, a few did and these were very dependable with consistent recruitment. Habitats occupied by later post-larval stages were also simulated; these were also found inhabited.

With this knowledge about the behaviour of the post-larval stages, Ingle and Witham (1969) proposed a method of artificial cultivation that eliminates the time-consuming and costly procedure of rearing phyllosomas from eggs. The procedure is to (1) locate a protected bay in which postlarvae can be obtained, (2) install an artificial habitat to

attract the postlarvae, (3) remove postlarvae from the habitat to holding ponds daily, (4) provide large quantities of small articles of a porous texture as a sanctuary for the juveniles, and (5) feed regularly. After the postlarvae have passed through the smallest, more vulnerable stages, the animals could be kept in the pond until ready for marketing, released into larger enclosures to forage and be fed on a supplemental diet, or released into public fishing areas.

4.2 American or Maine lobster

The American lobster, *Homarus americanus*, is one of the most popular decapods marketed in the United States and commands a premium price because of the decreasing yield in recent years (Hughes, 1968). Researchers at the lobster hatchery, established by the Commonwealth of Massachusetts on Martha's Vineyard off the heel of Cape Cod, have been intensively studying the possibility of culturing the lobster commercially. The present practice is to collect egg-bearing females from lobstermen and to allow them to hatch their eggs in hatching tanks. Hatched lobster fry are collected from these tanks and placed in special rearing tanks until the bottom-crawling stage. Water circulators in the rearing tanks keep the water moving, thereby preventing accumulation of larvae in the corners. The fry are maintained on a diet of finely ground clams or frozen adult brine shrimp. Survival rate has been estimated to be about 30 per cent, although in one season the survival rate was as high as 43 per cent. Causes of mortality have been traced to supersaturation of dissolved nitrogen in the water, which causes fatal gas diseases, to lethal ions of metals such as copper, to copper- and lead-based paints, and to insecticides in the vicinity of the tanks. When the lobsters reach the fourth moulting stage, they are released in selected areas along the coast of Massachusetts. Little is known about the fate of the hatchery-reared lobster after release.

Data collected by hatchery biologists over the years have indicated the possibility of commercial rearing of lobster from egg to adult (Hughes, 1968). One of the most important breakthroughs to potential lobster culture involves the production of second generations by hatchery-reared adults. Until recently, none of the successfully mated females produced fertilized eggs; however, by deepening the water in the female's tank to allow coverage of at least 18 inches (45.7 cm), hatchery biologists found that the female successfully laid and fertilized her eggs. Other data vital to a commercial lobster culture operation show that lobsters from the same batch grow at different rates, that temperature influences the lobster's metabolic rate so that they reach marketable size in less time, and that hatchery lobster can reach legal size in 3 years compared to 6 years in the ocean. These data all indicate that lobster culture is a definite possibility.

I. Regional and Country Reports

4.3 Clams

The clam is another invertebrate that has great potential for sea farming. Iversen (1968) reported that the hard clam, *Mercenaria mercenaria*, or "quahog," is farmed only to a limited extent in the United States, mainly along the Atlantic coast. The hard clam and the soft clam, *Mya arenaria*, or "long-necked clam," are both suitable for farming, although they are not as desirable as oysters as the object of sea farming because of their slower growth rate, the difficulty encountered in collecting seed, and the lower market price. Experiments carried out at Florida State University revealed that the hard clam grows rapidly in the warmer Florida waters and that marketable size of 2.5 inches (6.4 cm) can be attained in 2 years instead of the 5 years required in colder waters.

5 FISHES

The farming of marine species of fish has not progressed at the same rate as the farming of fresh-water species in the United States. One of the species which has been the object of intense research is the Florida pompano, *Trachinotus carolinus*.

In a report on the progress and potential of fish mariculture in the United States, Iversen and Berry (1969) presented new data on availability and ecology of beach-caught fry of the Florida pompano, a species which they believe has great farming potential in terms of market value, palatability, consumer demand, and research progress (Berry and Iversen, 1967). Iversen and Berry (1969) cited the work of Moe *et al.* (1968) and that of Finucane (1968) as contributing substantially to our knowledge of the biology, ecology, and farming potential of the pompano.

Iversen and Berry (1969) found that the Florida pompano fry were most abundant on low-energy beaches (those with a long gradual slope), whereas few fry were found on steep, high-energy beaches with heavy surf. They also found higher abundance of pompano fry in conjunction with falling tides and noted that abundance was greatest from about New Smyrna Beach north to St. Augustine on Florida's east coast.

Marine scientists at Batelle Memorial Institute's Florida Marine Research Laboratory near Daytona Beach have found from their studies on pompano culture, that feeding pompano five times a day at a rate of 10 per cent of their body weight per day, produces very rapid growth (Anon., 1968). Batelle scientists, who have been able to triple the size of surf-caught fingerlings after only 2 months in captivity, used four rectangular tanks 50 x 80 ft (15.2 x 24.4 m) and two circular tanks 20 ft (6.1 m) in diameter, all of which were 6 ft (1.8 m) deep, for their culture experiments.

Recent Progress in Coastal Aquaculture in the United States

Finucane (1970) also reported rapid growth of pompano in captivity; the best growth during a 6-month period was obtained by feeding a commercial trout feed. Stocked at a rate of 1 000 fish/acre (2 470/ha) pompano in ponds grew at a rate of 1.25 inches (3.2 cm) and gained more than 1 oz/month (28.4 g/month). Experiments with juveniles at St. Augustine, Florida, showed that with proper diet and control of water quality, the fish can be grown to a weight of about 1 lb (453.6 g) in less than a year.

Florida pompano can withstand extreme turbidity, rapid changes in pH and oxygen concentration as low as 3 ppm (Finucane, 1970). Other qualities which favour pompano for farming are their tolerance to close confinement and rapid recovery from injuries in salt water impoundments.

In experiments at the Miami Seaquarium, Iversen and Berry (1969) found that mortality of the young pompano varied, but they believe that death rates can be held to less than 10 per cent by minor improvements in the food and artificial environment and by adequate preparation to meet emergencies such as those resulting from mechanical failure, human error, epizootics or hurricanes. They also found beach-caught juveniles infested with cestodes, nematodes, monogenetic and digenetic trematodes, and sporozoans. To control the monogenetic trematodes, which damaged the epithelial layers of the gills and apparently interfered with respiration, Iversen and Berry (1969) applied routine prophylactic treatment with copper sulphate.

Temperature has been shown to be another of the critical factors affecting pond production of Florida pompano (Finucane, 1970). Experiments on pompano culture at the National Marine Fisheries Service Biological Laboratory at St. Petersburg Beach, Florida, revealed that the fish cease feeding at 13.9° C (57° F) and die at 10° C (50° F). Captive fish have survived in temperatures from 13.9° to 32.8° C (57° to 91° F), but water temperatures of 23.9°-25° C (75°-77° F) were reported to be ideal for good growth of the juveniles. Finucane (1970) reported that one of the best areas for pompano culture is the Florida Keys, where water quality and temperature are ideal.

Providing a suitable diet appears to be another critical problem in pompano culture (Finucane, 1970). None of the diets tested sustained maximum growth and low mortality and a unique diet especially formulated for pompano is needed before commercial farming on a large scale is possible.

To maintain commercial production of Florida pompano, it is also desirable to induce spawning and develop hatchery techniques to rear the fish from eggs to marketable size. Finucane (1970) reported that spawning has been induced by injecting ripe fish with chorionic gonadotrophin, but the spawned eggs have not been hatched as yet.

I. Regional and Country Reports¹

Iversen and Berry (1969) believe that intensive research should be started on artificial fertilization and on the rearing of larvae through the critical period following the yolk-sac stage. Subsequent genetic experiments could concentrate on improving the stocks with respect to rapid growth and disease resistance.

Not all the problems associated with pompano culture are technological or scientific in nature. Hull (1968), reporting on his observations on fish farms during a visit to Florida, emphasized that legal problems will undoubtedly hinder the rapid development of mariculture within the State. Large-scale capture of pompano fry, removed at a rate of 15 000-20 000 fry in one seining operation, has brought not only protests from the people living along Florida's east coast, mainly around St. Augustine, but also from sport and commercial fishermen (Hull, 1968; Iversen, 1969). Reacting to these protests, the Florida Board of Conservation recently imposed a restriction on the number of young that can be collected on public beaches, to stock private pompano ponds (Iversen, 1969). Hull (1968) stated that for pompano culture to succeed on a large, commercial scale, the fish will have to be spawned and cultured in captivity. But the sport fisherman, who traditionally has had the right to travel over the water surface in search of game fish, undoubtedly will question the legality of closing off navigable waters along the coast for the protection and convenience of the fish farmer. The pompano farmer also needs to anticipate problems in marketing, preserving and distributing his products. Iversen (1969) believes that the lack of trained personnel has also hindered progress in mariculture.

Among other species of fish receiving increasing attention as the object of mariculture is the salmon. In the State of Washington, early attempts at salmon farming in the 1950's were unsuccessful as problems with high temperatures, oxygen deficiency, disease, and inadequate food supplies all contributed to the failure to culture salmon in salt water enclosures (Anon., 1970). Recently, however, scientists from the National Marine Fisheries Service headed by Dr. Tim Joyner of the Biological Laboratory at Seattle, Washington, and from Oregon State University under the leadership of Dr. William J. McNeil, have produced evidence that salmonid fishes can be acclimated to salt water culture. Research at Oregon State University has shown that fry of selected races of most species of Pacific salmon can be acclimated to salt or brackish water. National Marine Fisheries Service scientists have successfully reared coho salmon, *Oncorhynchus kisutch*, in net enclosures floating in Puget Sound, where the fish grew from 0.7 to 10 oz (19.8 to 283.5 g) in less than 6 months. The results of feeding tests showed that conversion of food to flesh was very efficient: 1.5 lb (680.4 g) of wet pelleted feed produced 1 lb (453.6 g) of fish. The

success of this rearing experiment was attributed to the use of floating pens moored in water with a significant tidal flow. The water, stable in temperature and rich in oxygen due to constant mixing, flowed in volumes large enough to carry away waste products and to help reduce transmission of disease.

As outlined by Drs. Joyner and McNeil, the way to a potentially profitable salmon culture operation would be to transfer hatchery-reared fry to nurseries where they can acclimate to salt water, rear them to fingerling size, and then transplant them to floating pens in coastal areas for rearing to a marketable size of about 8-12 oz (226.8-340.2 g). Taste tests have revealed that 10-oz (283.5-g), pen-reared coho are an excellent product, and, in the opinion of those who have tasted them, the flesh is superior to that of rainbow trout.

Bardach (1968b), who summarized information on fish culture experiments at La Jolla, California, reported that more than 20 species of marine fish have been reared from egg through metamorphosis to the adult form. Research on marine fish culture at La Jolla concentrated on the problems of rearing pelagic fish larvae in confinement and supplying large quantities of food. Studying the biology of very small, transparent larvae was also an important phase of the investigation. Success in developing the techniques of mass rearing has resulted in culturing many thousands of Pacific mackerel, *Pneumatophorus diego*, sardine, *Sardinops caerulea* and anchovy, *Engraulis mordax*.

During the experiments at La Jolla, one major problem—that of feeding—was overcome by the development of a technique for supplying very small food organisms at the time of complete yolk absorption (Bardach, 1968b). Food was supplied in large quantities so that larvae of low mobility could find food in all parts of the aquarium. Sardine larvae, for example, searched about 0.06 cubic inch (1 cc) of water per hour at the onset of feeding and required a minimum of 4 food organisms/hr to survive. As the larvae grew, larger particles of food consisting of copepods were required; the scientists collected the copepods, which gathered at night around a 1 000-watt underwater lamp. After the larvae were large enough to consume zooplankters larger than 0.01 inch (0.25 mm), supplemental feeding of *A. salina* was started.

The experiments at La Jolla also showed that the quantity of food present in the environment plays a subordinate role in larval growth rates; rather, it is the individual and species genetic potentials, which are in turn moderated by water temperatures, that are of primary importance (Bardach, 1968b). Bardach also pointed out that a slight increase in larval size is correlated with an increase in size of food particles eaten and in the ability to move farther per minute of swimming in search of food; hence, efficiency of living increases with

I. Regional and Country Reports

size. Sardine-like larvae required about 30 days from onset of feeding to metamorphose to the adult form, whereas mackerel-type larvae metamorphosed to the adult form about 7 days after onset of feeding.

In one experiment involving 4 000 fry, it was found that at the onset of omnivorous feeding, Pacific mackerel larvae eliminated all other slower growing species, and within 9 days after hatching there was only a 50 per cent survival as a result of intraspecific predation (Bardach, 1968b). Problems of a nonbiological nature further reduced the remaining 2 000 fry to about 400 fish after 3 months. Six months after hatching, supersaturation of air in the sea water killed all but a few fish. Length and weight of 341 dead fish averaged 7.9 inches (200 mm) and 3.9 oz (110 g). On this basis, it was estimated that the yield would have been 0.6 lb/ft³ (3 kg/m²) of water or a projected 14 short tons/acre (31 metric tons/ha) at a minimum.

There are a number of other species of fish that have been mentioned by Iversen and Berry (1969) as suitable for farming, such as the Atlantic permit, *Trachinotus falcatus*, spotted seatrout, *Cynoscion nebulosus*, red drum, *Sciaenops ocellata*, red snapper, *Lutjanus aya* or *L. blackfordi*, grey snapper, *L. griseus*, and summer flounder, *Paralichthys dentatus*. Considerable interest is also being shown in mullet, *Mugil cephalus*, as a species suitable for mariculture in the United States, although there are a number of obstacles to be overcome. Iversen (1968) stated that the biggest disadvantage to farming this species is the very low market value in many areas of the United States, excepting Hawaii. Other problems associated with mullet culture are the high cost of collecting the young at sea in order to stock the fishponds and the sorting that is necessary to control predators.

The Hawaiian pond culture of marine fishes, primarily mullet, milkfish, *Chanos chanos*, tenpounder, *Elops hawaiiensis*, and bonefish, *Albula vulpes*, provided a substantial portion of the fish consumed in Hawaii in former years (Hiatt, 1947). But in recent years, the pond catch comprised only a small fraction of the total fish production, the result of a decline in the number of ponds now used for fish mariculture. In 1969, for example, only 19 988 lb (9 metric tons) of fish and crustaceans were produced in ponds, compared to the total marine catch of 9 708 146 lb (4 400 metric tons). According to the Hawaii Division of Fish and Game, there are presently only two ponds in commercial operation on the island of Oahu and three on the island of Molokai. Other species of marine fishes and crustaceans caught in the ponds include carangids, *Caranx* sp., mountain bass, *Kuhlia sandvicensis*, barracuda, *Sphyrnaena barracuda*, threadfin, *Polydactylus sexfilis*, white crab, *Portunus sanguinolentus*, red crab, *Podophthalmus vigil*, Samoan crab, *Scylla serrata* and shrimp, *Bithynis grandimanus*.

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EXPLORATORY BOTTOM TRAWLING IN HAWAIIAN WATERS

by

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ABSTRACT

The exploratory bottom trawling cruises were made in Hawaiian waters on the Bureau of Commercial Fisheries research vessel TOWNSEND CROMWELL between October 1967 and May 1968. The cruises were conducted in cooperation with the Hawaii Institute of Marine Biology, University of Hawaii.

An area totaling 4,974 sq km was covered during the exploratory surveys. Approximately 42 percent of this area or 2,106 sq km was judged to be trawlable; 2,281 sq km were untrawlable and 587 sq km were marginally trawlable. A relatively large uninterrupted area of trawlable bottom was found north of Maui.

One hundred and nineteen trawl drags were made on the cruises primarily using the Gulf of Mexico-type flat shrimp trawls of various sizes.

The species with the greatest commercial potential caught during the surveys was a penaeid shrimp, *Penaeus marginatus*. Relatively good catches of this shrimp were made in depths between 97 and 234 m around Molokai and in an area off the north coast of Oahu.

INTRODUCTION

Oceanic islands, such as the main Hawaiian Islands, are characterized by having narrow shelves, which have been appropriately called insular shelves in contrast to continental shelves. The insular shelves surrounding the main Hawaiian Islands can be traced to 549 m (300 fm.), although most of the shelves extend to depths less than 91 m (50 fm.) (Shepard, 1948, p. 141-142). Depths of 1,826 m (1,000 fm.) can be found as close as 11 km from shore (Fig. 1). Thus, a priori, a large demersal resource would not be expected in Hawaiian waters, based simply on the extent of the shelf around the islands.

In an early investigation of the demersal resources of the Hawaiian Islands, a study of the fauna to a depth of 1,826 m was conducted from March to August 1902 on the ALBATROSS, research vessel of the U.S. Fish Commission (Gilbert, 1905). This survey covered an area around Hawaii bounded by lat. 18° to 26° N., long. 156° to 172° W. Most of the published records of deep-water fishes and invertebrates from Hawaii are based on specimens caught on the ALBATROSS survey. Although several species of potential commercial importance were discovered on that survey, none was taken in significant quantities. The types of gear used on the ALBATROSS included tangles, dredges, and beam trawls, which probably were not very efficient by today's standards. The ALBATROSS also lacked modern depth-sounding equipment, which is almost a necessity for efficient trawling.

Between October 1967 to May 1968 the Bureau of Commercial Fisheries Biological Laboratory, Honolulu, Hawaii, in cooperation with the Institute of Marine Biology, University of Hawaii, conducted a series of three exploratory bottom trawling cruises on the Bureau's vessel, the TOWNSEND CROMWELL, in Hawaiian waters. The purpose of the cruises was to investigate the demersal fish and invertebrate resources around the Hawaiian Islands down to a depth of 914 m (500 fm) using more efficient trawling gear than that used on the ALBATROSS.

Very little bottom trawling has been done in areas similar to the Hawaiian Islands. The results obtained on our cruises will provide information on conditions that can be expected in trawling around oceanic islands elsewhere. This report will discuss catches of the species with possible commercial potential.

GEAR AND METHODS

Prior to our surveys, very little information existed on bottom conditions around the Hawaiian Islands with respect to bottom trawling. The strategy adopted in conducting our surveys was to first locate the most promising areas on the basis of depth data and bottom notations on navigational charts, and then conduct detailed echo-sounding transects in these areas. Bottom grab samples were taken to confirm trawlable bottom as indicated by the echograms. The surveys were restricted to depths of 914 m (500 fm) or less.

The primary sampling gear was the Gulf of Mexico-type, flat, shrimp trawl (Bullis, 1951, p. 8). The size of the trawls (length of the head rope) ranged from 6.70 m (22 ft.) to 16.76 m (55 ft.). The trawl was connected to a single towing warp by a bridle 46 m long. Doors (otter boards) of various sizes included the Gulf of Mexico-type, wooden, chain doors measuring up to 1.52 by 0.76 m. Most of the drags were made with a pair of aluminum "V" doors measuring 0.96 by 1.83 m. Also used were a 21.34 m (70 ft.) Gulf of Mexico-type, semiballoon, shrimp trawl (Greenwood, 1959, p. 4) and a 400-mesh, eastern, otter trawl (Greenwood, 1958, p. 12). The otter trawl was used with two towing warps and a pair of aluminum doors measuring 1.52 by 2.44 m (5 by 8 ft.).

For single-warp dragging, the trawl was towed from the starboard side of the vessel off a hydrographic boom. For double-warp dragging, two gallows on the starboard side were used. The trawl was set out at a speed of 4 to 6 knots and the cable was released at a rate of 18 to 45 m per minute. The depth-to-cable-out (scope) ratios ranged from 1.9 to 4.2. The trawl was fished for 13 minutes to 4 hours (time trawl was on bottom). Trawling speed usually ranged between 1.0 and 4.7 knots.

TRAWLING AREAS AND CATCH

The area of the bottom to a depth of 914 m round the Hawaiian Islands is estimated to be approximately 44,076 sq km. An area totaling 4,974 sq km was surveyed during the exploratory surveys (Fig. 1). Of the area surveyed, 2,106 sq km (42.3 percent) were considered to be trawlable, 587 sq km were marginally trawlable, and 2,281 sq km were untrawlable.

The largest uninterrupted expanse of trawlable bottom, comprising about 1,063 sq km, was found north of the island of Maui. The bottom here sloped gently from about 274 to 523 m. Drags as long as 4 hours were made in this area.

Trawlable bottom was found around Molokai off the northwest, west and south coasts, and also in Pailolo Channel, between Molokai and Maui. South of Oahu, an area totaling 429 sq km and a small area comprising 14 sq km north of the island were found to be trawlable. Patches of trawlable ground were also found in Kealaikahiki Channel between Lanai and Kahoolawe. The waters around the island of Hawaii were a disappointment, for only small areas of trawlable bottom were found there. Furthermore, off the north coast of Hawaii sugar cane debris on the bottom tended to clog the trawls. The sugar cane debris also hampered the sorting of the catch.

A total of 119 trawl drags was made around the islands. Ten of the drags were unsuccessful owing to torn nets and loss of gear. A summary of the trawl drags in the various areas is found in Table I.

For the development of a commercial fishery a penaeid shrimp, *Penaeus marginatus*, was the most promising species caught during the exploratory cruises. This shrimp was known to occur in Hawaiian waters from the explorations of the ALBATROSS in 1902 (Rathbun, 1906, p. 902) but only small numbers were taken on that survey. *P. marginatus* compares favorably in size with the penaeid shrimps of the major fisheries in the southeastern United States. The larger females number 18 to 20 to 1 kg (8 or 9 to 1 pound), heads on.

The distribution of *P. marginatus* on trawlable bottom around the Hawaiian Islands is shown in Figure 2. The shrimp were caught in depths between 27 and 234 m on sandy and sand-mud substrate. The catch ranged from less than 0.45 to 16.10 kg per drag. Good catches were made off the west and in Pailolo Channel. Good catches were also made off the north coast of Oahu. The area north of Oahu has some rough spots on the bottom, however, and must be considered marginally trawlable since two nets were damaged on the exploratory drags made here.

Adequate data are not available to make seasonal comparisons of *P. marginatus* catch rates. Comparisons of day and night catches can be made, however. Off the north and west coasts of Molokai and off the north coast of Oahu, the night catches were almost always better than the day catches. The depth in these areas ranged from 97 to 183 m. In Pailolo Channel, where the depth ranged from 183 to 254 m, however, little or no difference between the day and night catches was evident (Fig. 3). Springer and Bullis (1952) made similar observations on the brown shrimp (*Penaeus aztecus*) in the Gulf of Mexico. They noted that this species is generally taken at night but that differences in the catch rates were not as well defined in the deeper parts of the shrimp's range.

Other potentially valuable species caught in the shrimp trawls included several species of small (20 cm) deep water flatfishes belonging to the family Bothidae and Pleuronectidae. The catches of individual species of these flatfishes were small but, collectively, up to 13.61 kg per drag were taken. The flatfishes were widely distributed around the Hawaiian Islands (Fig. 4). The best catches were made in Pailolo Channel. Also caught were small numbers (up to 14 per drag) of spiny lobster (*Panulirus japonicus*) and portunid crab (*Portunus sanguinolentus*); the latter caught at a maximum rate of 30 per drag. The lobster and crab were taken primarily on sandy bottom in depths to about 128 m off Molokai, Oahu and Lanai. These lobster and crab command premium prices in the markets in Hawaii.

ACKNOWLEDGEMENTS

I thank P.J. Struhsaker of the Hawaii Institute of Marine Biology, University of Hawaii, for his assistance in all aspects of the trawling operations, and Captain G.H. Miller and the crew of the TOWNSEND CROMWELL for their cooperation in carrying out the surveys. I also thank J.B. Richards, J.P. Christofferson, and A.E. Murchison who are, or were, associated in varying capacities with the University of Hawaii, for participating in portions of the exploratory cruises.

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Table I

Distribution of trawl drags around the Hawaiian Islands

Area	Number of drags	Average depth range (m)
Oahu		
Off north coast	6	97-113
Off south coast	3	594-640
Maui		
Off north coast	17	48-523
Hawaii		
Off coast of Kawaihae	5	260-356
Off north coast	6	229-869
Molokai		
Off north coast	7	110-137
Off west coast	13	181-183
Off south coast	3	265-274
Penguin Bank	3	62-66
Pailolo Channel between Molokai and Maui	29	183-254
Kealaikahiki Channel between Lanai and Kahoolawe	27	97-427



Fig. 1 The main Hawaiian Islands, showing the 1,826-m (1,000-fm.) and 183-m (100-fm.) depth contours. The crosshatch shows the areas surveyed.



Fig. 2 The distribution of *Penaeus marginatus* on trawlable bottom around the Hawaiian Islands.

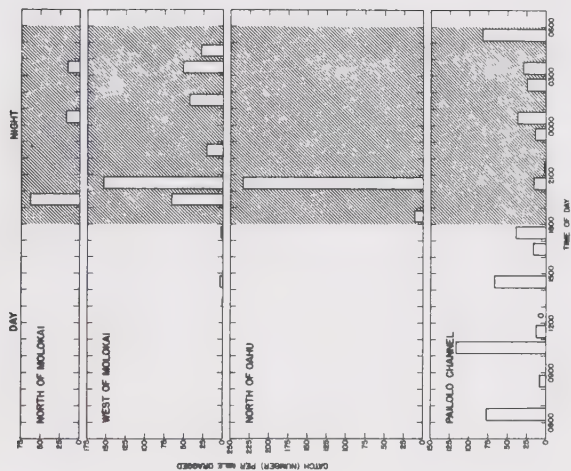


Fig. 3 Day-night variation in catches of *Penaeus marginatus*.

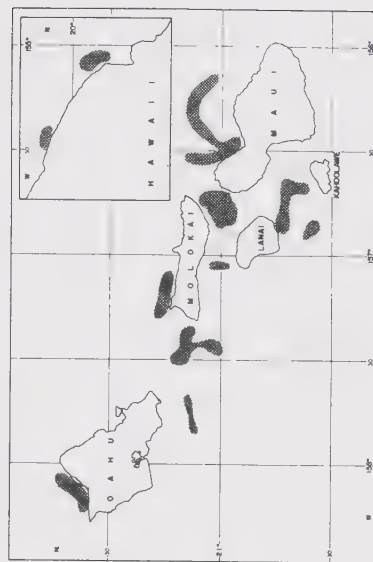


Fig. 4. The distribution of flatfish catches around the Hawaiian Islands.

